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TORONTO HARBOUR NUMERICAL MODEL

VERIFICATION AND PRELIMINARY STORM RUNOFF RESULTS

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Ministry of the Environment
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SUMMARY AND CONCLUSIONS

The two-dimensional numerical model of Toronto Harbour has been operated using input data from a July, 1977 storm runoff period. The model was run for two conditions: (a) absence of, and (b) presence of, storm water runoffs from the city waterfront sewers. This enabled the verification of the input physical parameters used in the earlier model runs (Poulton, 1977), and the qualitative assessment of the impact of runoff from the waterfront sewers.

Comparison of observed currents measured at a central harbour location with modelled results at nearby locations, showed that the general trend of observed currents is simulated but that short-term changes (of order less than a few hours) are not well simulated. Considerable smoothing of model data was required to remove oscillations of periods below 15 minutes in order to achieve adequate comparison.

Plots of model total dissolved solids (TDS) concentrations with and without waterfront sewer runoff show a significant effect of storm water runoff across the north shore of the harbour early in the simulation. Several hours later, the increased TDS was transported down the east side of the harbour and across the island shoreline. These results are only preliminary in nature, due to the lack of detailed time-dependent concentrations data. In particular, the storm water TDS was kept constant with time, rather than assuming the first-flush effect (high concentrations at the beginning of a storm, followed by reduced concentrations as flow continues). This variation with time may not be typical of important pollution parameters such as suspended solids or bacteria. In addition, the runoff period selected was characterized by a rainfall which was far more intense than average. The flow rate from one outfall had to be approximated for a portion of the model interval due to lack of observed data.

Several options for future work are suggested. This includes use of a stormwater model to provide inputs of flows and pollutant concentrations at the stormwater outfalls discharging directly to the harbour. Parameters which could be used are BOD, fecal coliforms and total suspended solids (the latter in conjunction with a model of bottom sediment erosion and resuspension). Modifications of the input data could be designed to study the effects of water management options in Toronto Harbour, including alternatives such as creation of a new channel south of the Island Airport, changes in cooling water flow rates at the Hearn generating station, modifications of the outer harbour which would restrict exchange in the East Gap, and various control schemes for operation of the waterfront interceptor sewer.

INTRODUCTION

In the initial report on Numerical Modelling in Toronto Harbour (Poulton, 1977), the application of short-time scale recording meter data to the two-dimensional depth-integrated hydrodynamic and water quality model was discussed. The model was operated using winds, current meter and water chemistry meter data recorded during the period November 7-11, 1975, a period which included two episodes of increased flow in the Don River due to rainfall-related runoff.

The model has now been operated for the period July 6 - 8, 1977, an interval which included two storm runoffs of large magnitude. The model was verified by running it with the 1977 input data, using the physical parameters used in the 1975 model, in the absence of storm water input from the city waterfront sewers; the modelled currents were compared against an independent set of currents measured within the harbour at a fixed point. Subsequently, a qualitative estimate of the impact of storm water runoff was obtained by including the input from the city waterfront sewers and plotting modelled concentrations at several time intervals. As in the 1975 model, the quality parameter used was total dissolved solids (TDS) as measured by conductivity. This was used as it is largely conservative (non-reacting), and real-time data were available at 20-minute intervals in the two gaps and the Keating Channel.

The results as presented in the storm water runoff section of this report must be regarded with caution as a number of assumptions were required during the modelling. Firstly, the variation of conductivity with time in runoff may not be typical of important pollution parameters such as suspended solids or bacteria. It was necessary to assume a constant value for the storm runoff concentration in the absence of detailed time-dependent data. The flow rate from one outfall had to be approximated on July 6 due to lack of observed data. In addition, it was necessary to assume an average flow rate for the Hearn generating station and adjust this to maintain a relatively constant water level in the harbour. This may not be accurate because the flows in the two gaps are based upon

measurements of currents at only one point in space. Currents may not be homogeneous across the gaps and may be depth-stratified; measurements taken during summer 1979 suggest depth-stratified flows may occur for a portion of the time. Furthermore, the storm flow observed during the model period is also not typical of normal runoffs; the one-day rainfall on July 6 (53.6 mm or 2.1 inches) was exceeded on only two other occasions in 1977 and has not been exceeded since. The two-day rainfall (70.9 mm) has not been exceeded on any other occasion since October 1973, and is indeed higher than many monthly total precipitation figures. Consequently, based on these results, no firm conclusions should be drawn regarding the influence of storm water runoff. Simulations will be undertaken using more typical data gathered during the 1978 monitoring period.

DESCRIPTION OF MODEL

The two-dimensional model presently used consists of the coupled depth-integrated equations for momentum, continuity and mass balance. These are solved by finite-difference techniques in a space-staggered grid. The equations and their method of solution have been described elsewhere (MOE, 1974); details of the application of real-time recording meter data to the model in Toronto Harbour have also been described (Poulton, 1977).

The numerical grid used is shown in Figure 1, and the locations of measured current and water quality meter data used as input and validation data are shown in Figure 2. Results from the east and west gaps and the Keating Channel were read directly into the model at intervals of 10 minutes (currents) or 20 minutes (chemistry), while the results from the internal points were used for model calibration; i.e. they were used for comparison purposes, in order to adjust the values for physical parameters (surface stress and bottom roughness) and were not entered directly into the model.

Model verification consists of operating the calibrated model with a set of input data which is completely independent of the input data used for model calibration (Hinwood and Wallis, 1975). The previous

report (Poulton, 1977) comprised only model calibration; in this report model verification is provided by operating the model with the same physical parameters as previously used, but with current and chemistry meter data obtained in the 1977 field season.

COMPARISONS BETWEEN MODELLED AND OBSERVED DATA, 1975 RESULTS

Subsequent to preparation of the previous report, the data comparison was extended to include the plotting of observed and modelled currents and water quality as a function of time, and also Fourier norms (least-squares error differences between observed and modelled currents) (Poulton, 1979); these methods will be described briefly here before the model verification is discussed. As these methods are also used with the verification (1977) data set described herein, their application to the calibration data set is summarized. Firstly, the model u and v velocity components at the grid location previously used for cross-correlation (Poulton, 1977) were combined to yield a resultant speed and direction, and these were plotted alongside the observed values. This comparison is shown in Figure 3. Except for the short period of observed currents up to 14 cm s^{-1} at about 18 h of modelled time, the modelled speeds compared very well with the observed speeds. Lack of model precision at this time may be due to either unresolved depth variations of currents or too long an interval between input wind speeds, which may have missed a large but brief gust. Agreement of the observed and computed directions is favourable provided the speeds are greater than about 2 cm s^{-1}; at lower speeds it is possible that the current meter vane responds less slowly to changes in direction. Such low current speeds are also below the threshold speed for the type of current meter in use. Beyond 36 h, calibration data were not available.

Figure 4 shows the comparisons of modelled conductivity with observed data obtained from the independent monitoring station 128. The independent data were smoothed with a binomially weighted running mean over five values in order to remove random fluctuations caused by the digital precision of the measuring instrument ($\pm$ 1 umho cm^{-1}). For the first 72 hours, agreement between modelled

and observed results is very good except for some observed fluctuations between about 32 and 48 hours, which the model failed to simulate. Between 72 and 80 hours, however, the model predicted a far greater decrease in conductivity than what was observed; following this the two curves were similar in shape but displaced laterally due to the large model decrease. Apparently the model overestimates the extent of lake water advection across the southern part of the harbour (Poulton, 1977, Figure 10a). The overall result, however, does show the model to be a reasonable predictor of time variations in water quality over periods of hours to days; however at points far removed from the locations of input data, fluctuations within minutes are not simulated. The reason for this shortcoming is not known.

Fourier norms were used by Allender, Berger and Saunders (1977) to compare observed and modelled currents in Lake Michigan. The Fourier norm is the standard deviation of the residuals (difference between observed and modelled) velocity component over the modelled time period. A good correspondence between measured and modelled data is indicated when its value is minimized. To indicate whether the model is a reasonable predictor of currents, the magnitude and time variability of observed currents can be assessed by substituting zero speeds for the modelled data. If the model is performing well, the model norms should be less than the norms from zero. These are calculated according to the following relation:

$$F = \left[\sum_{t=\Delta t}^{N\Delta t} \frac{(u_o - u_m)^2}{N} \right]^{1/2}$$

where: u_o = observed velocity component (U or V)
u_m = modelled velocity component
N = number of time steps

Fourier norms for the u (parallel to east gap) and the v (parallel to west gap) components of modelled velocities are given in Table 1. That the modelled norms for the v component are considerably less than the norms from zero indicate that the model is apparently a good predictor of currents at this time. In the case of the u component, the modelled and zero norms are of similar magnitude; these norms are smaller as the principal axis of the current directions at this location is closer to the model y axis (direction of the v component).

INPUT DATA SET FOR MODEL VERIFICATION

In 1977, the robot monitors were operated at the two gaps and Keating Channel from mid-June to early September. Data were recorded at a 20-minute interval. Current meters were operated at the gaps and the internal validation points from June 22 to August 16. In addition, streamflow data from the Don River at Todmorden and wind data from the Toronto Island Airport, both recorded at a 60-minute interval, were used as model input. The locations of these input points, except for Todmorden (about 2 km upstream from the Keating Channel) are shown in Figure 2.

For purposes of estimating the effect of storm water runoff, hourly gauged flows in the sewers leading to the harbour outfalls were obtained from the City of Toronto Department of Public Works. These data were used together with average conductivity values measured in the harbour slips adjacent to the outfalls during the summer of 1977. The values used are given in Table 2, and the model grid locations of storm water input are shown in Figure 1. These were considered the best approximations available despite the fact that most values were recorded during dry weather; the absence of real-time data for the model period precluded the use of any better data. This fact is discussed in more detail later.

In order to provide a reasonable estimate of the effects of storm water runoff, a period was selected from the available data in which a significant runoff of Don River water of varying conductivity, as well as storm water runoff, occurred. The selected period was July 6-8. Figure 5 showns the Don River flow and Keating Channel conductivity for this period and Figure 6 shows the wind data as measured at the Toronto Island airport. Figure 7 shows the observed storm water runoff volumes for outfalls TH-11 and TH-15 for July 6-7. There was no runoff on July 8; consequently the test of the effect of storm water runoff ended at 48 h modelled time (midnight July 7). For most of the modelled period, more than 50% of the storm water entering the harbour was discharged through these outfalls (excepting that carried by the Don River). All conductivity values were converted to total dissolved solids for model input by multiplying by 0.65.

The modelled interval used represents a time of summer stratification, during which a three-dimensional model should ideally be used. Only mediocre agreement with observed currents was obtained in Hamilton Harbour using the two-dimensional model during summer stratification (MOE, 1979). However, Toronto Inner Harbour is shallow enough that summer stratification is intermittent, and frequently is confined to the lowest two or three metres of the water column. This is illustrated by temperature profiles (Figure 8) taken during the 1977 field season from a location near the centre of the harbour. It was thus hoped that the two-dimensional model would still perform reasonably under the field conditions.

To complete the description of model input data, a value for the outflow through the ship canal to the Hearn intake was required. Kohli (1978) reported values of 2.6 - 2.7 x 10^6 m^3 day^{-1}, or 30 - 31 m^3s^{-1} according to mass balance calculations based on 1975 data. P. Wiancko (Ontario Hydro personal communication) stated that the Hearn G.S. measures flows on a cumulative weekly basis. Average flow was 23 m^3s^{-1} for the week ending July 6 and 30 m^3s^{-1} for the week of July 7 - 13. As was done with the 1975, a figure was used which represented a near zero change of water level during the modelled interval. The values used were 25 m^3s^{-1} in

the absence of storm runoff, and 26.7 m^3s^{-1} including storm runoff. Also as done previously, the model was spun up for 6 h prior to the start of real-time data input. During this period the wind was held constant at its initial value and all source and boundary flows were linearly interpolated from zero to the initial value.

RESULTS AND DISCUSSION

Model Verification: Run In Absence of Storm Runoff

The model was run for the 72 h time interval as described in the previous section. Physical parameters used were identical to those used in the previous work (Poulton, 1977), i.e. wind stress coefficient = 0.0032; Manning's n = 0.040, 0.045, 0.050, and 0.060, used on the grid as previously shown (Poulton, 1977, Figure 7); mass balance dispersion coefficient = 0.93 m^2s^{-1}; and time step lengths of 20 s for hydrodynamics and 60 s for water quality. As no independent time series data were available for water quality, only the hydrodynamic portion of the model was verified. The water quality results obtained were used for comparison with the storm water runoff model and are discussed in the next section.

Observed and modelled velocities were compared by converting the calculated u and v components into a resultant speed and compass direction, and plotting these together with the observed currents as a function of time for meter location 128. The u and v components were smoothed over a 30 min. interval in order to remove short-term fluctuations, before resultants were calculated. As was done in the previous modelling studies (Poulton, 1977; MOE, 1979), several model grid locations in the vicinity of the current meter were tested. The locations selected for the final comparison are shown in Figure 9. These represent the best fit to observed data as obtained by summing the differences between observed and modelled velocities for several rows and columns near the validation point.

Comparisons of observed and modelled velocities are given for point A in Figure 10 and point B in Figure 11. For the first 7 h at point A, the model direction is inconsistent with the observed direction,

and the speed is too low. This is probably related to the length of spin-up time used, as will be discussed further later. From 7 to 54 h modelled time, the general trend of the observed hydrodynamics is followed; however, the modelled current direction does not follow the short-term changes in the observed direction although it keeps fairly close to the average direction. During the last 18 h the modelled direction becomes incorrect at point A; for this reason comparison at point B is also presented. Agreement between observed and modelled currents at point B is poor for the first 30 h. For the remainder of the record, good agreement is found, except that the predicted shift in current direction during the last 12 h occurred about 6 h before the observed shift and was accompanied by very low current speeds (less than 1 cm s^{-1}). Overall, the model-meter agreement is better at point A for the first half of the modelled period (Figure 10a) and at point B for the last half (Figure 11b). Thus a tendency for the location of the model point with the best fit to observed data, to shift in time, was observed here as was seen in Hamilton Harbour (MOE, 1979).

At times, the modelled direction was fairly constant while the observed direction showed short-term oscillations while at other times the modelled direction contained short-term oscillations which were not observed. Difficulties in simulating currents at short-time intervals may be related to sub-grid scale turbulent dispersion, which affects both currents and water quality. Leendertse and Liu (1977) have suggested that vertical and horizontal turbulent exchanges play an important role in determining sub-grid scale dispersion, and they have introduced modifications to their three-dimensional model to account for these effects. Neglect of such effects could account at least partly for the failure of the present model to simulate accurately these short-term changes.

Oscillations which did appear in the modelled current direction were highly dependent upon the time interval of smoothing of model data. Short-term oscillations in time-series data produce apparent longer-term oscillations when the time-series is sampled at longer intervals, unless the time-series is smoothed before sampling. This phenomenon is known as aliasing (Jenkins and Watts, 1968). Figure 12 shows the autovariance density spectral analysis of model u and v velocity components sampled at a 1-minute interval for 24 hours from

comparison point A. The dominant periods (12.8, 8.3 and 6.6 minutes) agree with those observed in the previous model spectrum (Poulton, 1977) which was run at a 2-minute interval. Sampling the model output at the 10-minute current meter interval without smoothing causes apparent oscillations with intervals of up to an hour due to aliasing; to suppress these apparent oscillations the model data are smoothed with binomial coefficients over a 30 to 40 minute interval before sampling.

The possibility that additional aliasing of shorter periodicities may have occurred, was negated by an additional spectral analysis at a 20 s interval, which did not reveal any additional higher frequency peaks. These peaks are believed to represent internal harbour oscillations (Poulton, 1977); however, no confirmation of this hypothesis has yet been obtained.

These short-term modelled oscillations were even more intense at model grid points near the other internal validation point (129; Figure 2). For this reason, verification of the model at this location was impossible despite the existence of current meter data at this point.

Model comparison was also performed using Fourier norms, as already discussed for the 1975 data period. As agreement between observed and modelled results changed with time at the two locations used, calculations were performed separately for each 24-hour period. The results, given in Table 3, are in general agreement with the plotted data. Poor performance (model norms greater than zero norms) for point B in the first 24 h resulted from the lack of direction agreement; the early disagreement at point A is reflected in the high value of the v component norm. Better performance in the second 24 hours is reflected in the u component norm, while the v norms show the effect of the average direction being slightly different from that observed. During the last 24 hours, the Fourier norm shows the better performance of point B and the poor agreement now found at point A.

Within the capability of the present models and current metering program, it is felt that the results presented here represent a realistic model verification. This is significant as very few such

models have been verified (Hinwood and Wallis, 1975). The capability of a model to simulate real conditions is limited by the validity of the input data and the assumptions used in deriving the model. The effects of errors in calibration have not been studied in detail (Hinwood and Wallis, 1975). In particular, the assumption of homogeneity with depth is questionable for the time period used as stratification, though unstable, did exist (Figure 8). The fact that maximum horizontal velocities can be far higher than vertically averaged velocities (for example, Lick, 1976), is illustrative of the limitations involved in operating a two-dimensional model. This fact undoubtedly limits severely the accuracy of model-meter comparisons by the methods used.

In 1978, current and water chemistry meters were operated from September 12 to October 13. As may be expected, the water column was far more homogeneous with depth during this time interval. On five of six profiles taken during this interval in the inner harbour, the temperature difference from top to bottom was below 1.3^{o}C. This period should therefore prove more suitable for accurate verification than the one presently used. It is suggested that verification be repeated in conjunction with the runoff modelling studies proposed for this period.

Effect of Spin-up Time

As already mentioned, the model runs using both 1975 and 1977 real-time input data were performed with a six hour spin-up period. It was decided to test the effect of this spin-up period, by doing a separate run starting with July 7 data. The results were compared with the July 7 portion of the initial run (start July 6) by plotting speed and direction together as done with the current meter comparison. The result is shown for 24 h in Figure 13 at the validation point A. It shows that the direction is incorrect for the first 7 h on the July 7 start, and gradually shifts to values in agreement with the previous run over the next several hours. Speeds are also different for more than 12 hours. Similar tests with other grid points indicated differences persisting for up to 18 h. No differences were observed during an additional 24 h (not shown). It

is apparent that spin-up time should be increased from 6 h to as much as 24 h for results to be accurate from the beginning; comparing Figure 13 with Figures 10a and 11a suggests that the direction errors during the first 8 to 10 h may have been caused by inadequate spin-up time.

The model in its present form uses approximately 8 minutes of CPU time on the IBM 370/168 computer for a 24 hour run. Due to the expense of rerunning the model, it was decided to proceed with modelling the effect of storm water runoff, using the run as detailed here as a control run in the absence of runoff, despite the errors observed near the beginning of the run. Future work on modelling storm water runoff will include a longer spin-up time.

<u>Prediction of the Effect of Storm Water Runoff on Harbour Water Quality</u>

The model run already referred to was repeated for the first 48 h, including storm water runoffs as measured by the City of Toronto Department of Works at six outfall locations as shown in Figure 1. Flow data were missing for outfall TH-12 on July 6. From the observed flow rates on July 7, it was decided to estimate the flow rate of TH-11 as 0.1 * (sum of remaining overflows - 50,000 cfs). This formula produced a close approximation to the observed results at TH-12 for the portion of July 7 when overflow was observed there. The flow rates at two locations representing most of the discharge are shown as a function of time in Figure 7. No measurements of TDS concentrations in the storm sewers were available for the model period. Conductivity values were recorded in the slips adjacent to each outfall on three or four occasions during summer 1977. The average values obtained, given in Table 2, include the effect of dilution of storm sewer water by harbour water and moreover were in general obtained during dry weather when runoff did not occur. As these were not representative of conditions in the sewers, a constant value of 800 umho cm^{-1} was assumed for the storm water conductivity for an initial assessment of its effect. Flows and concentrations for the other source and boundary points were identical to those used in the initial model run, except that

the discharge to the Hearn Ship Canal was increased from 25.0 m^3s^{-1} to 26.7 m^3s^{-1} in order to keep the harbour water level approximately constant.

Modelled TDS concentrations are presented in figures 14-18 at 3-hour intervals of modelled time, for the periods of largest runoff. The initial result (Figure 14) depicts the situation at 15 h modelled time, or about 6 h following the commencement of runoff. Adjacent to TH-15, the TDS has exceeded 260 mg L^{-1}, while along the remainder of the waterfront the TDS is between 228 and 240 mg L^{-1}. Three hours later, following the peak storm water flows (Figure 7), TDS has exceeded 300 mg L^{-1} adjacent to TH-15 and 240 mg L^{-1} adjacent to TH-12 and 13. The zone of TDS $<$ 228 mg L^{-1} now occupies less than half the harbour, next to the islands (Figure 15a). This is in contrast to the case without storm sewer runoff (Figure 15b) where this zone occupies most of the harbour except the extreme east and west ends. In both cases, the large flow of relatively low conductivity water from the Don River has produced a region of rapid change in conductivity within the northeast part of the harbour, with the high TDS water that had originated from the Don River several hours earlier being diluted as it is pushed into the harbour. A similar effect was noted in the 1975 model study (Poulton, 1979). Because of the large flow volume from the Don River, the effects of the storm water discharges at TH-9 and TH-10 are obscured.

After 18 hours modelled time, the volume of discharge subsided rapidly. Figures 16a and b show that the zone of increased TDS due to runoff is largely confined to the vicinity of TH-12 and 15. The concentration is above 260 mg L^{-1} near TH-15. Although the zone in which the largest concentration gradient due to the Don River has changed very little during this interval, mixing of higher concentration water from the plume has increased the TDS concentration over most of the harbour to above 228 mg/L.

As very little runoff occurred during the next 18 h (Figure 7), very little difference was observed between the model cases with and without runoff, and no figures are presented for this interval. At

39 hours modelled time, a second storm had begun to produce additional runoff; the effect is shown in Figures 17a and b. At this time, the TDS concentration in the northeast part of the harbour had become more uniform. The Keating Channel was again occupied by higher TDS water (see Figure 5; the peak conductivity during this runoff event occurred at about 40 h modelled time). Higher TDS water (>240 mg L^{-1}) has been advected from the region of TH-10 south and west to the island shoreline. Some of this increased TDS must have originated from the Don River as areas of TDS 240 mgL^{-1} near the east gap and Hearn ship canal are also seen in the absence of storm sewer runoff (Figure 17a). It should be noted that the change in TDS within the island channels in Figure 17b is not significant as it originated from the contouring program and not the model. After 42 hours (Figure 18b) the area of TDS 240 mg L^{-1} has diminished considerably, though the effect of the runoff is still very much in evidence, mostly in the northeastern and southeastern parts of the harbour. After 48 hours (not shown), the TDS throughout the harbour is about 2 mg L^{-1} higher with storm sewer runoff and larger differences are observed only immediately adjacent to the outfalls. In addition to the effects of the storm water outfalls and Don River, the effects of lake-harbour exchange through the gaps can be seen in figures 16 - 18. The flow to the west gap was generally into the harbour, while the east gap tended towards alternating inflow and outflow during the modelled period. These flows influence the location of the 228 mg L^{-1} contour within the northwest part of the harbour, and near the southern end of the east gap.

This series of concentration contours has demonstrated the effect of runoff from the Don River at varying concentrations, and of storm outfalls at constant concentrations, on the Toronto Harbour water quality. It must again be cautioned that the results are only qualitative due to the lack of detailed concentration data. The storm period modelled was also characterized by a much larger runoff than usual, and the parameter modelled (TDS) is not entirely representative of important pollution indices. At this time, it is therefore not possible to draw quantitative conclusions about the

effects of storm runoff on Toronto Harbour water quality, although the results reported certainly do indicate the general water quality patterns which might be expected to occur.

Future Work

Additional work should be directed towards circumventing the disadvantages of the present work as already summarized. In particular, the use of constant storm sewer concentrations, and of the parameter TDS itself, must be questioned. A washout effect may occur within the storm sewers, similar to that in the Don River; i.e., the TDS concentration could reach a peak shortly after runoff begins and then could drop rapidly to values below the ambient harbour concentration. If this is so, lower concentrations would be observed across the north shore of the harbour during runoff than in the absence of runoff. A two-day storm water event sampling study on the Etobicoke Creek (Environmental Applications Group, 1977) showed high conductivities at the beginning of runoff, followed by decreased values. However, overall deterioration in water quality occured during the event, despite the decreased conductivity. Considerable increases were observed in BOD, suspended solids and total Kjeldahl nitrogen as the storm progressed. Several peaks in these parameters were found, including one near the time of maximum flow. Peak values could be related to specific sources, such as disturbance of the stream bank, storm sewers and surface runoff. Similar washout effects were observed with conductivity and several other parameters during studies of an East York urban catchment area (Dillon, 1979). Rimer et al (1978) also observed peak values of COD, suspended solids and total P to coincide approximately with the flow peak at locations characteristic of highly urbanized areas; they observed a washout effect even with these parameters at a rural location. Indeed, the Don River has been observed to be carrying large amounts of suspended solids during a runoff when the conductivity was below 300 umho cm^{-1}. These observations indicate a definite shortcoming in the use of total dissolved solids as a water quality parameter to simulate the effect of runoff on the harbour.

Other parameters should therefore be considered for future efforts at modelling effects of storm water runoff. In addition, the output of storm water models could be used for the overflow sources. The City of Toronto Department of Public Works has used the quality-quantity simulation (QQS) model of Dorscht Consultants, Germany, to model storm water runoffs to the harbour. This model produces detailed real-time output of flows and concentrations for individual storm events. Currently, BOD, total suspended solids and fecal coliforms have been modelled, but theoretically any parameter could be used provided reliable input data are available. Modelling of these parameters requires decay constants which may be available in the literature; at any rate, the model would have to be calibrated to actual conditions by adjusting the value of the decay constant in a manner analagous to that already done with the hydrodynamic model. Lick et al (1979) have studied sediment entrainment and deposition rates in Lake Erie and used the results in conjunction with a hydrodynamic model in order to predict the extent of bottom sediment erosion and redeposition. Such a model should also consider the effect of waves (Lick, 1976) on sediment resuspension. In order to do this, a model of wind-induced wave action (Donelan, 1979) would be required. It is possible that this method would be useful in modelling suspended solids in Toronto Harbour.

An adequate data base would probably be available during the September-October 1978 period for calibration of such a model. Several large runoffs occurred while current meters were in place; in addition, the QQS model has already been run for a large storm on September 18. Twice weekly nutrient and bacteria data are available adjacent to the storm outfalls and gaps in the harbour during this interval from the joint MOE-City Works Program. Intensive survey data are available for four days in early October including a runoff period. A preliminary study of the results of the MOE-City Works Program indicated high values for several parameters were observed on September 18 at many of the locations sampled. It certainly appears that modelling involving some of these parameters and dates should prove interesting.

In summary, several options of future work are available for continued numerical modelling efforts in Toronto Harbour. This

includes use of a storm water model to provide inputs of flows and concentrations of non-conservative pollutants at the storm water outfalls discharging directly to the harbour. Parameters which could be used are BOD, fecal coliforms and total suspended solids. It would be desirable to interface the present model with a model of bottom sediment erosion and resuspension (Lick, 1979) if suspended solids were used. Alternately, in the absence of proper decay data for non-conservative pollutants, the harbour could be modelled with total dissolved solids as measured by recording meters or predicted by storm water model results. Improved TDS results so obtained would serve as an indicator of time-dependent advective and dispersive processes and modifications of the model and input data could be designed to study the effects of possible options for pollution abatement.

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TABLE 1

Comparison of Observed and Modelled Currents, Toronto Harbour

by

Fourier Norms

Calibration (1975) Data Set

	U	V
Model:	119.1	485.1
Zero:	118.3	1311.0

Note: U direction is component parallel to East Gap

V direction is component parallel to West Gap

TABLE 2

Average observed conductivities at Toronto Harbour storm water outfalls, 1977.

Outfall	Conductivity (umho/cm)
TH-9	546
TH-10	445
TH-11	435
TH-12	409
TH-13	445
TH-15	455

TABLE 3

Comparison of observed and modelled
currents by Fourier norms, Toronto Harbour

Verification (1977) data set

Model Interval	U: Model Location A	U: Model Location B	U: Zero	V: Model Location A	V: Model Location B	V: Zero
0 - 24 h	248.9	834.0	784.3	887.9	1453.5	873.2
24 - 48 h	264.7	581.4	1240.0	630.2	824.4	637.0
48 - 72 h	885.5	386.8	454.9	618.9	152.3	197.5

Note: U direction is component parallel to East Gap
V direction is component parallel to West Gap

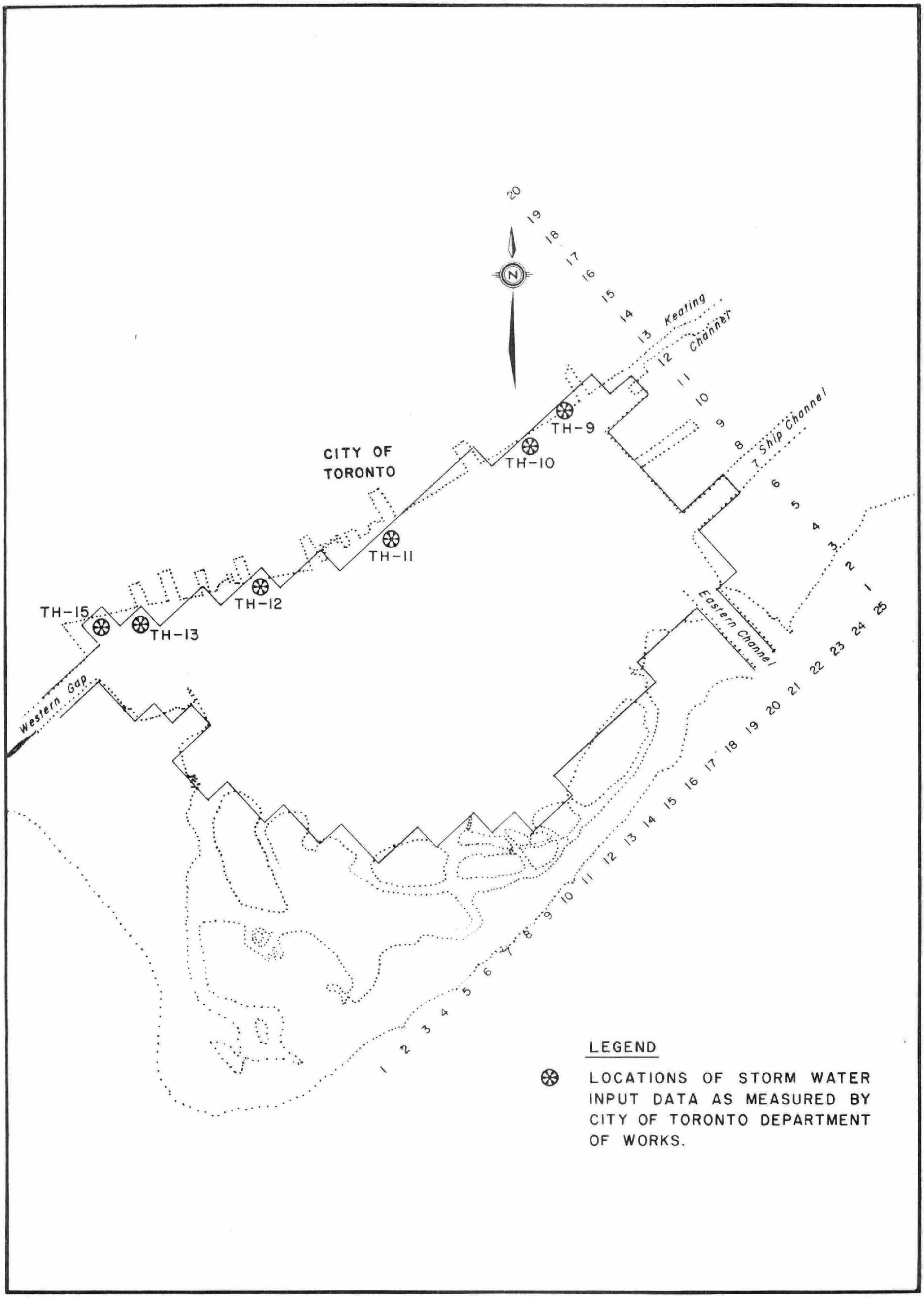


FIGURE 1 – TORONTO HARBOUR NUMERICAL MODEL GRID, INCLUDING LOCATIONS OF STORM WATER INPUTS.

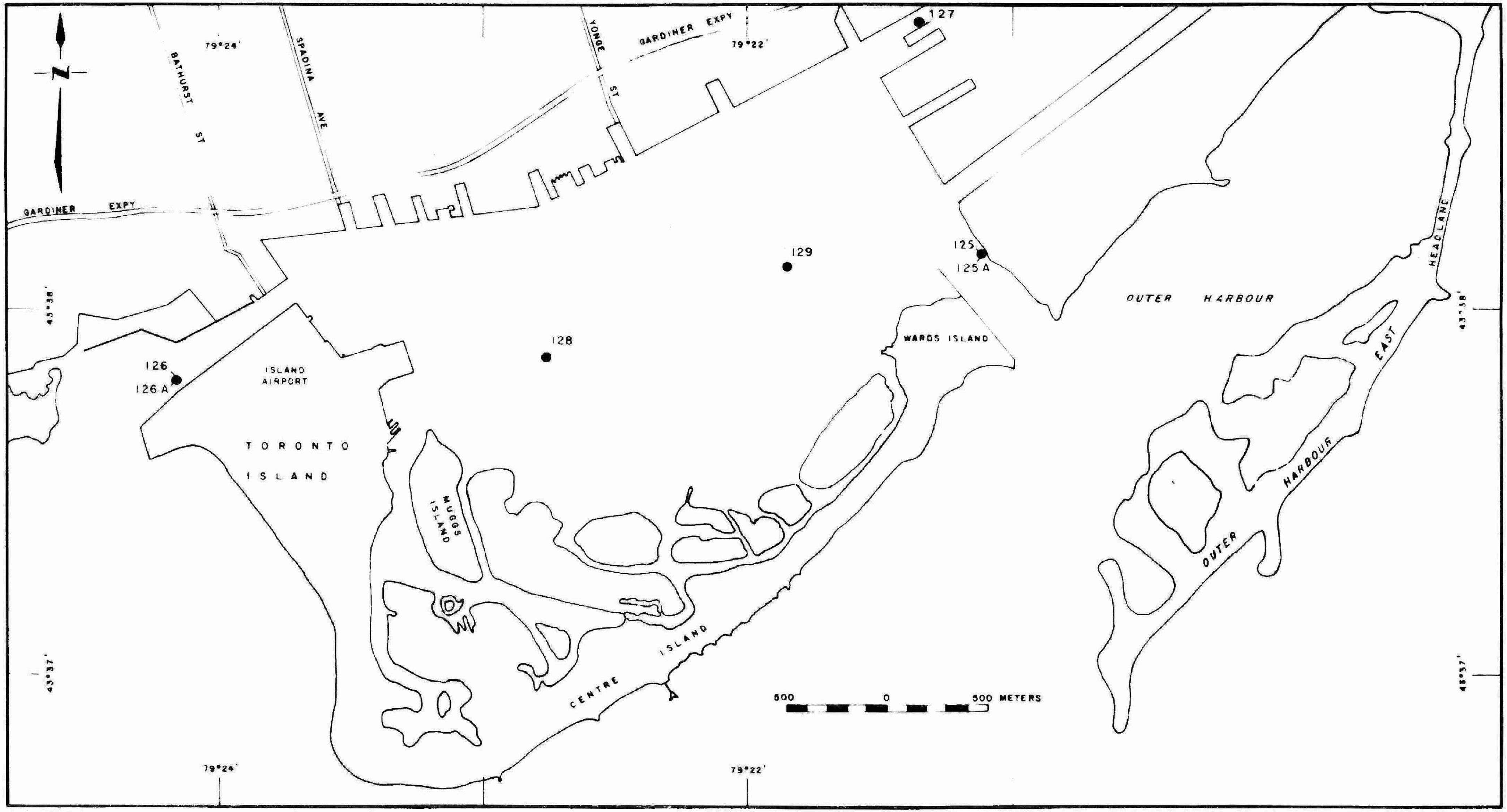


FIGURE 2 - LOCATION OF BOUNDARY AND INTERIOR MONITORING POINTS FOR TORONTO HARBOUR NUMERICAL MODEL.

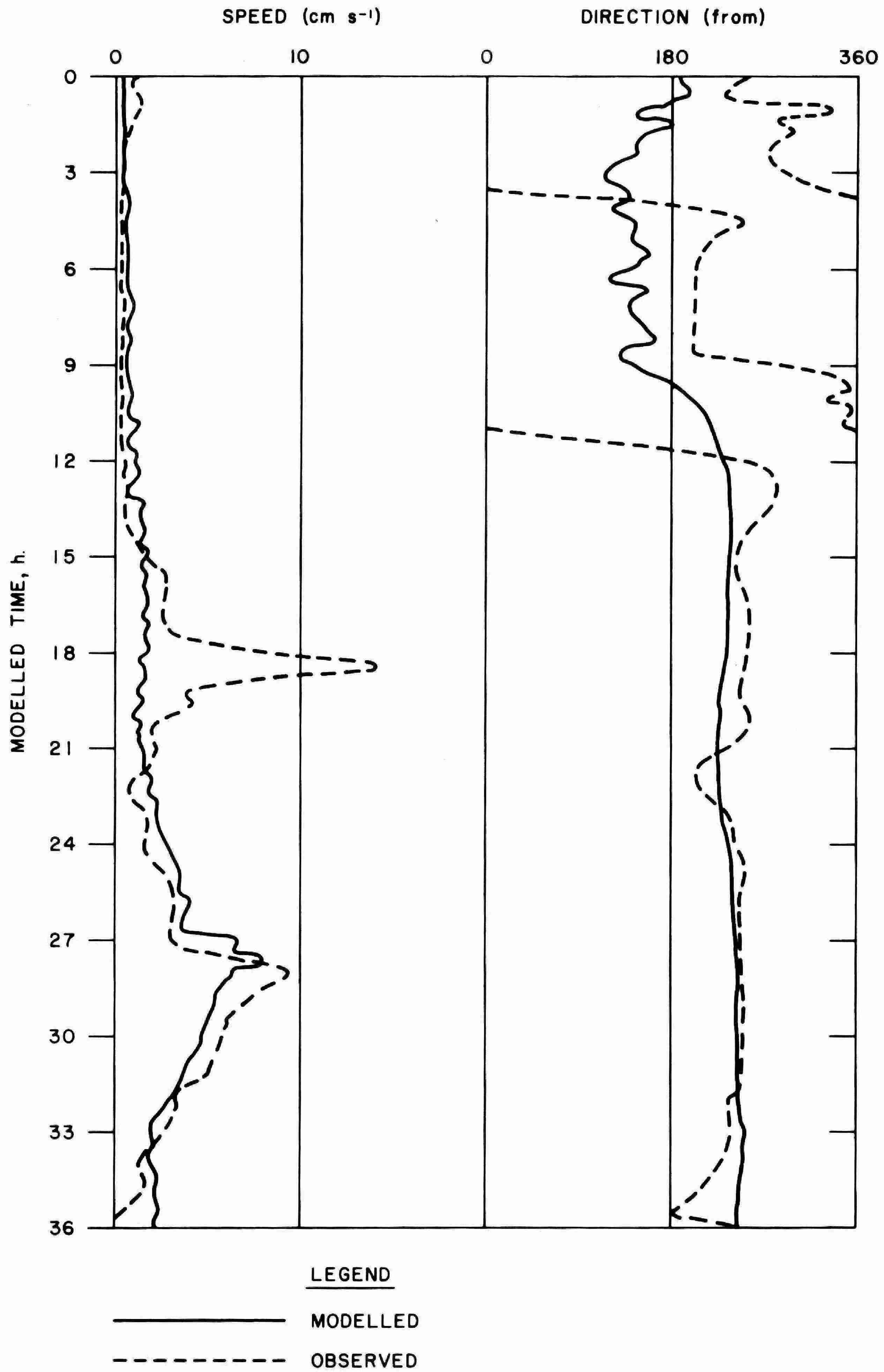


FIGURE 3 - COMPARISON OF OBSERVED AND MODELLED VELOCITIES FOR NOVEMBER 7-8, 1975, LOCATION 129.

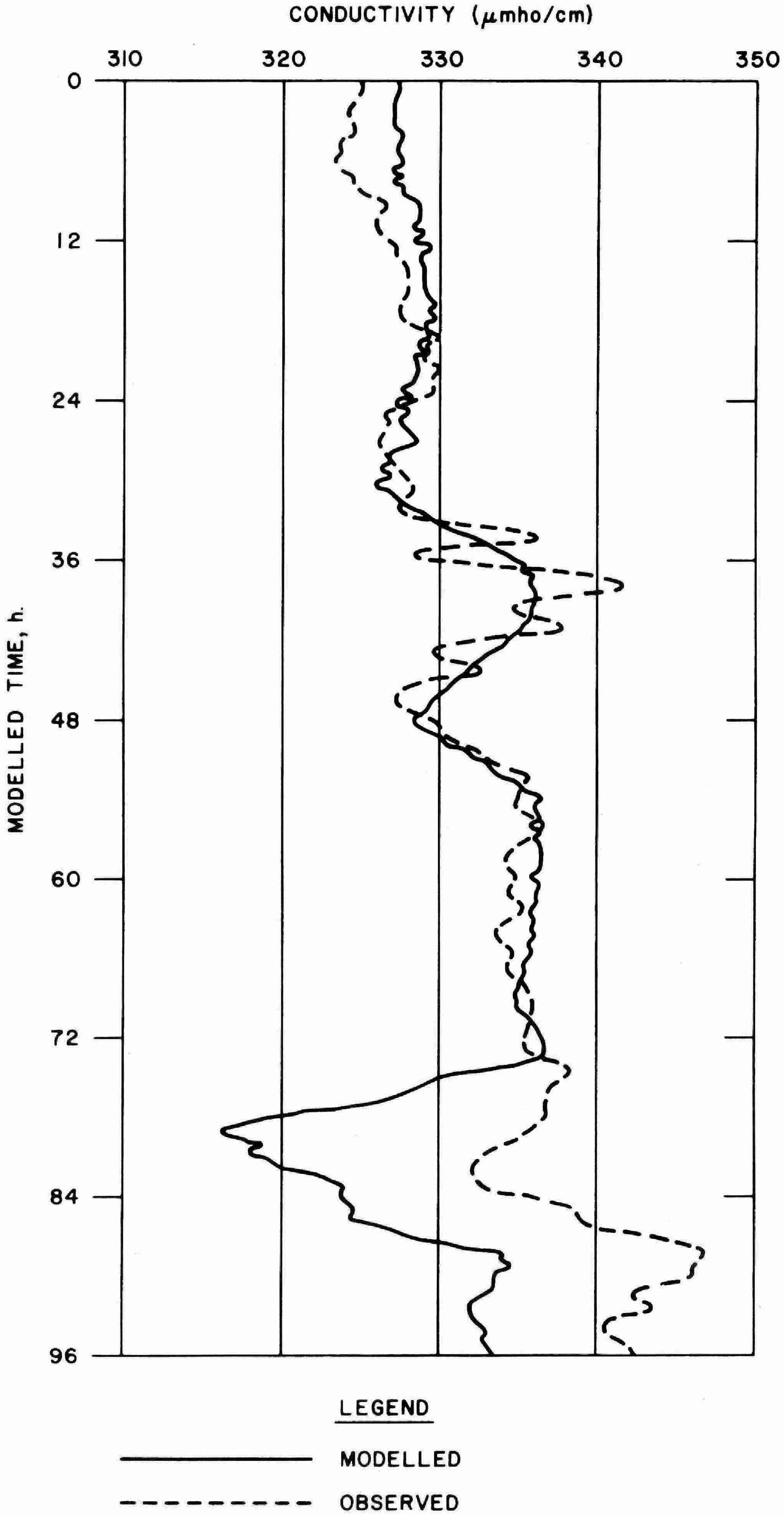


FIGURE 4 - COMPARISON OF OBSERVED AND MODELLED WATER QUALITY FOR NOVEMBER 7-11 1975 LOCATION 128.

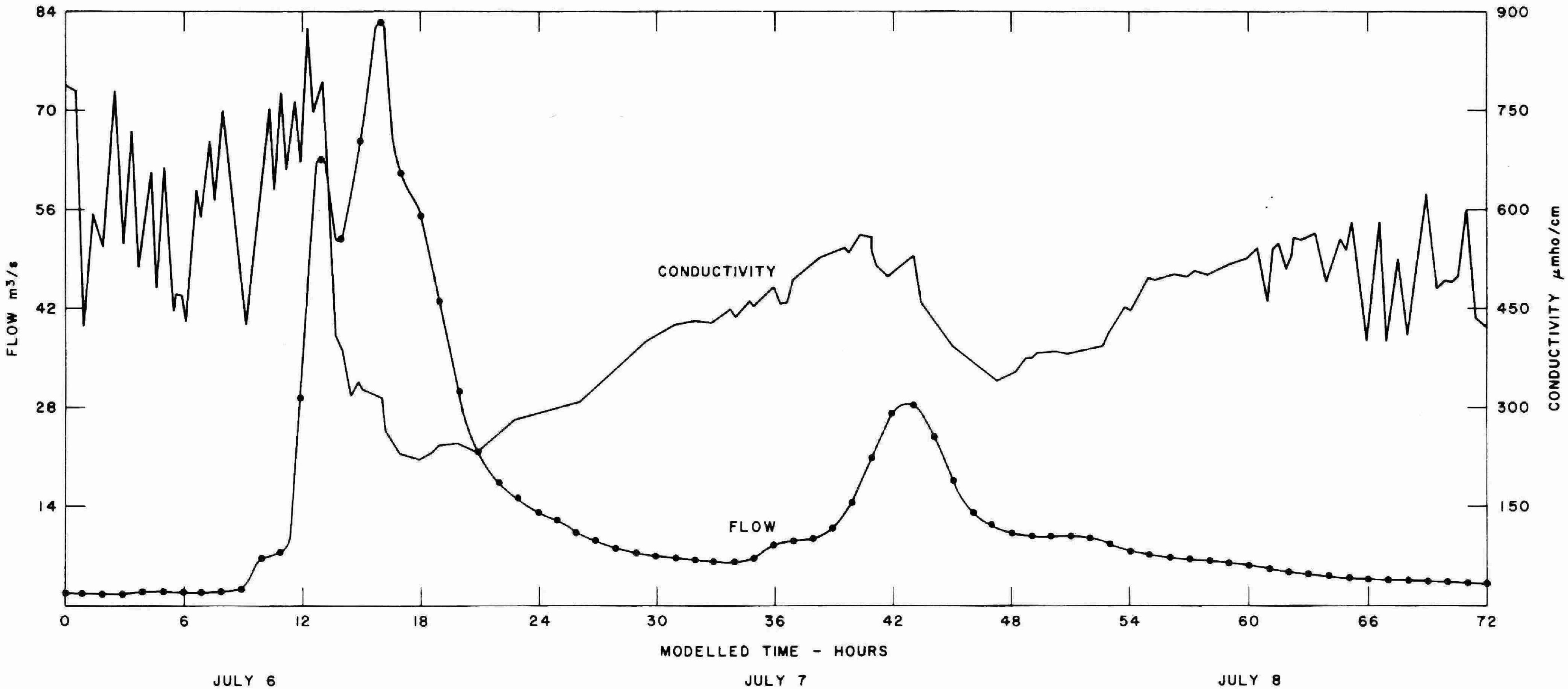


FIGURE 5 - DON RIVER STREAMFLOW AND KEATING CHANNEL CONDUCTIVITY, JULY 6-8, 1977.

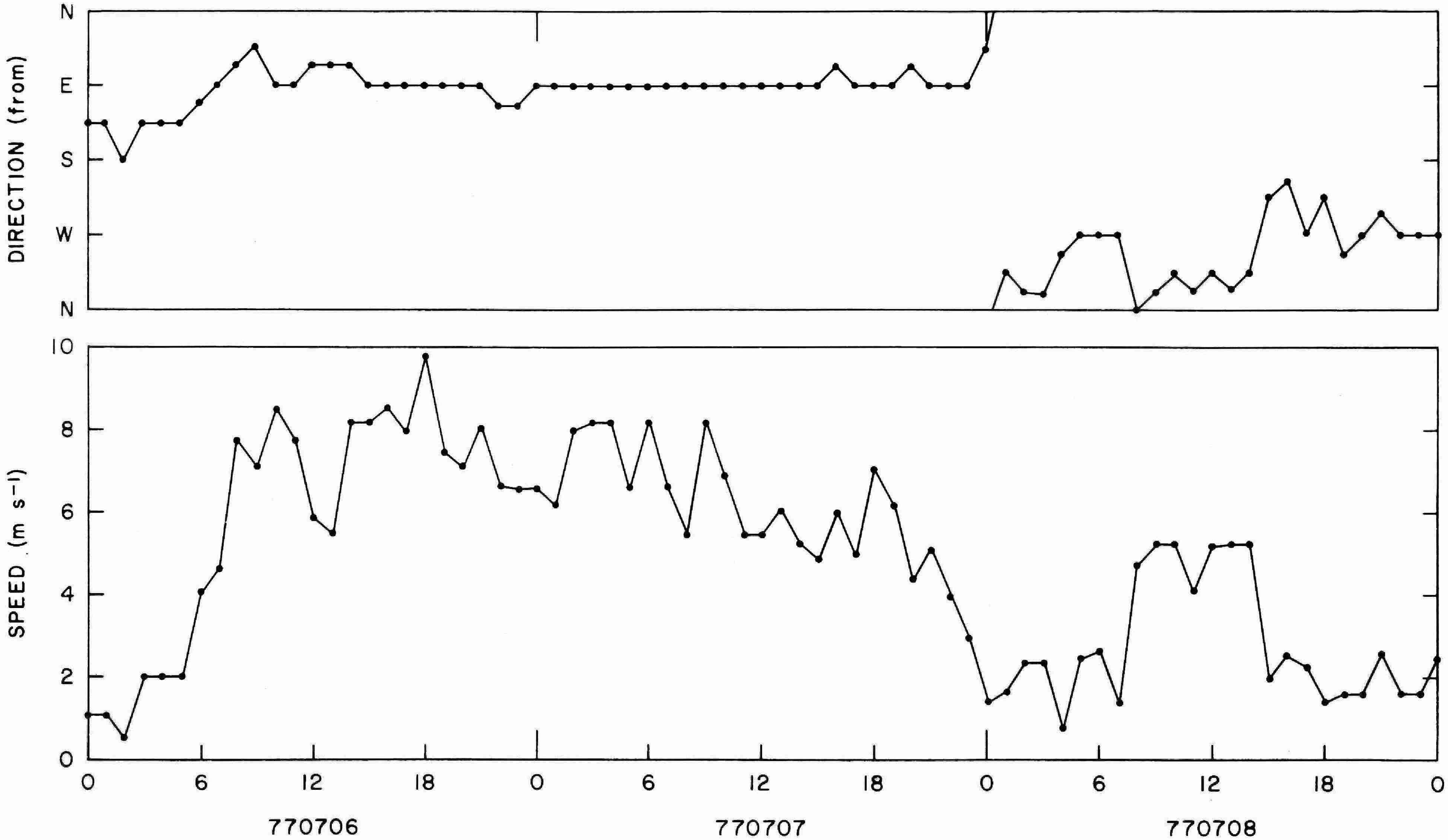


FIGURE 6 - HOURLY WIND DATA INPUT TO NUMERICAL MODEL AS MEASURED AT TORONTO ISLAND AIRPORT.

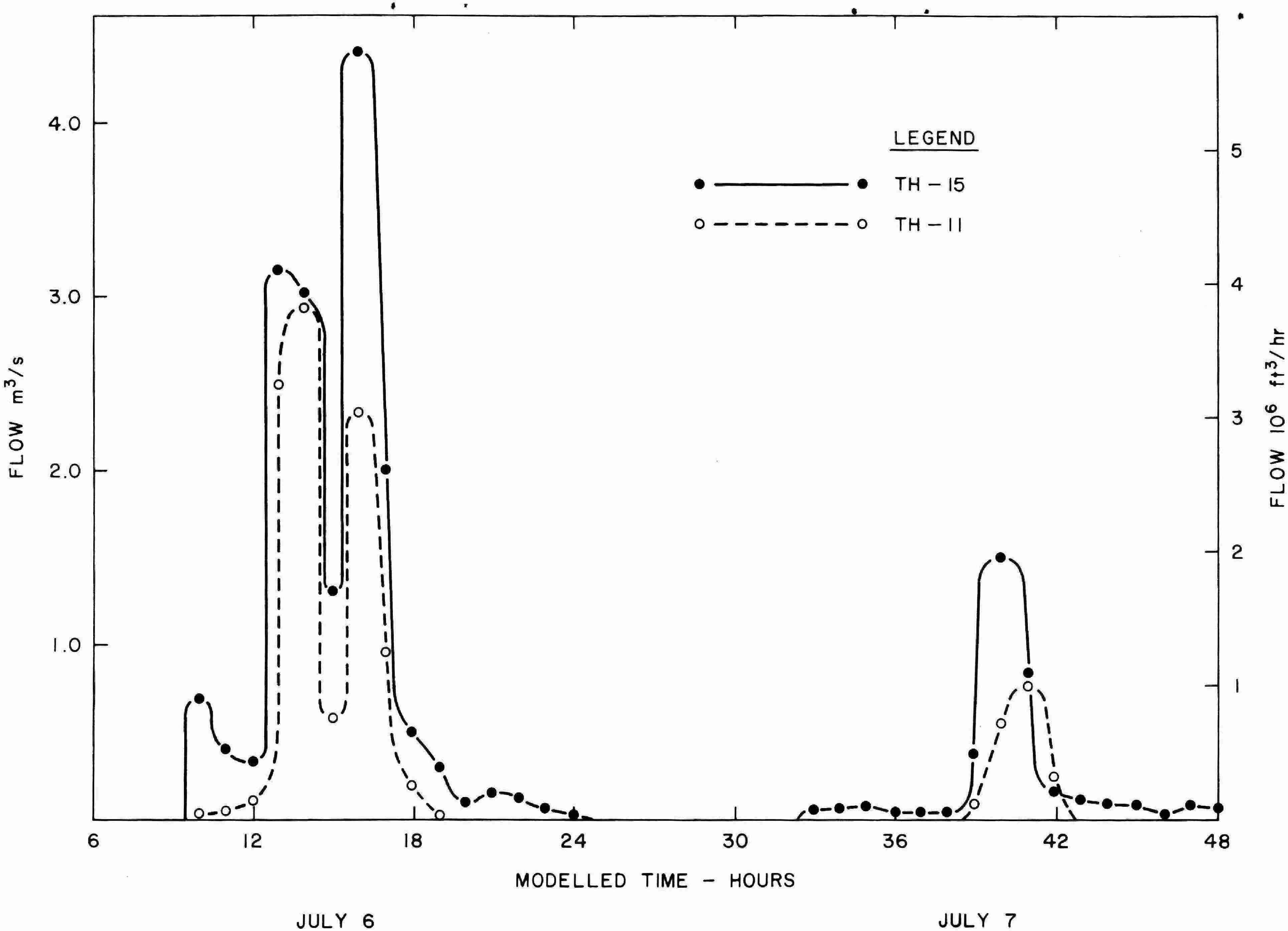
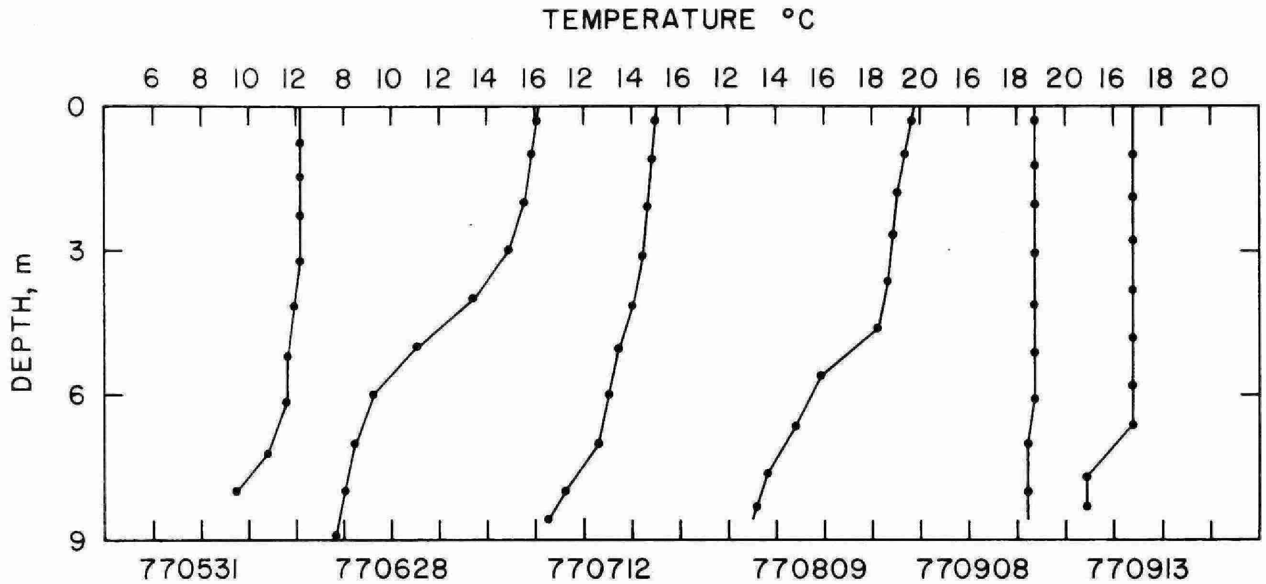


FIGURE 7 - OBSERVED STORM WATER DISCHARGE FLOW RATES TO TORONTO HARBOUR, JULY 6-7, 1977 (FROM CITY OF TORONTO DEPARTMENT OF PUBLIC WORKS).



NOTE: EACH PROFILE IS DISPLACED 6°C COMPARED TO THE PREVIOUS PROFILE.

FIGURE 8 - VERTICAL TEMPERATURE PROFILES OBSERVED IN 1977, TORONTO HARBOUR LOCATION 1364.

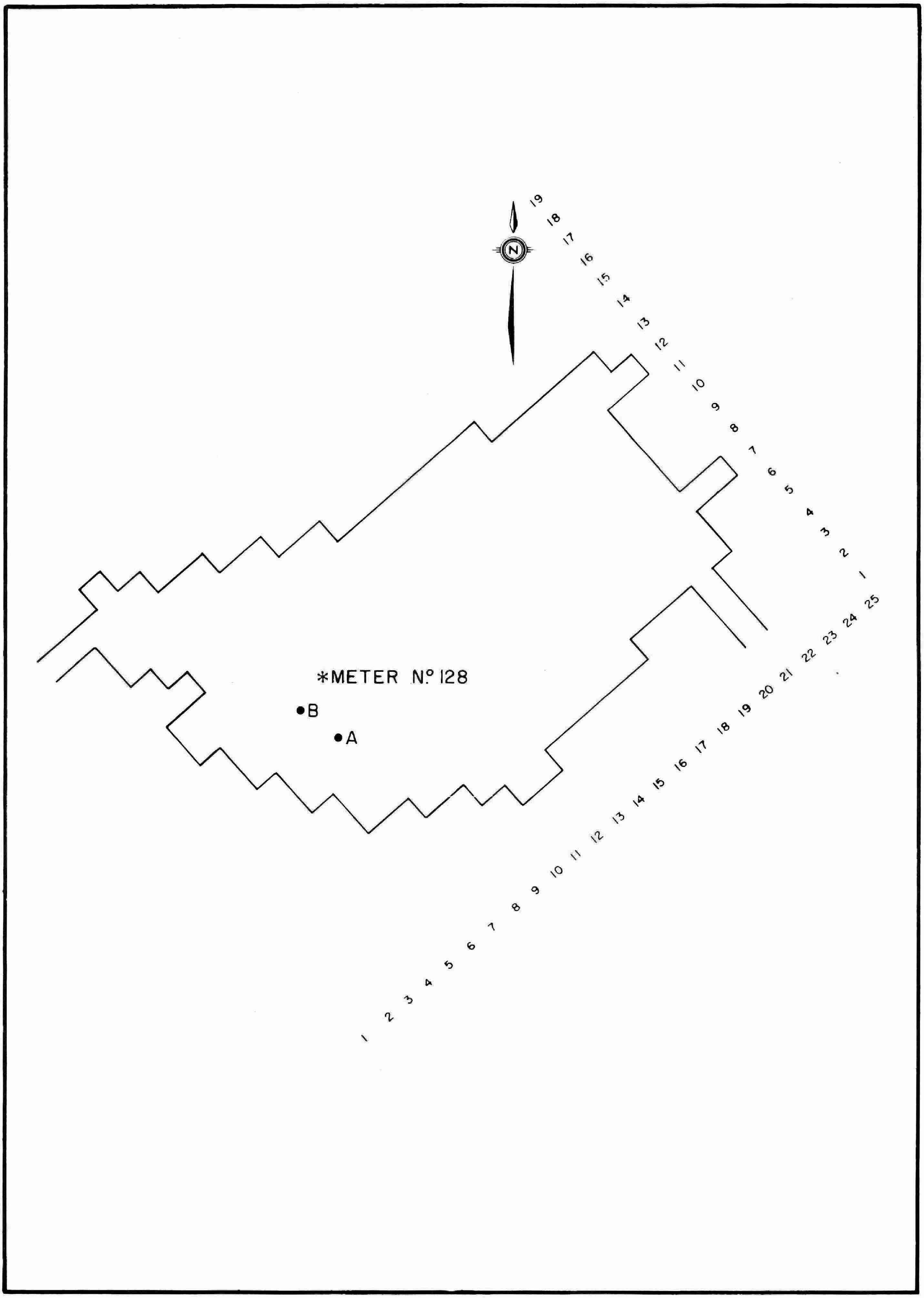


FIGURE 9 - LOCATIONS OF MODEL VALIDATION POINTS.

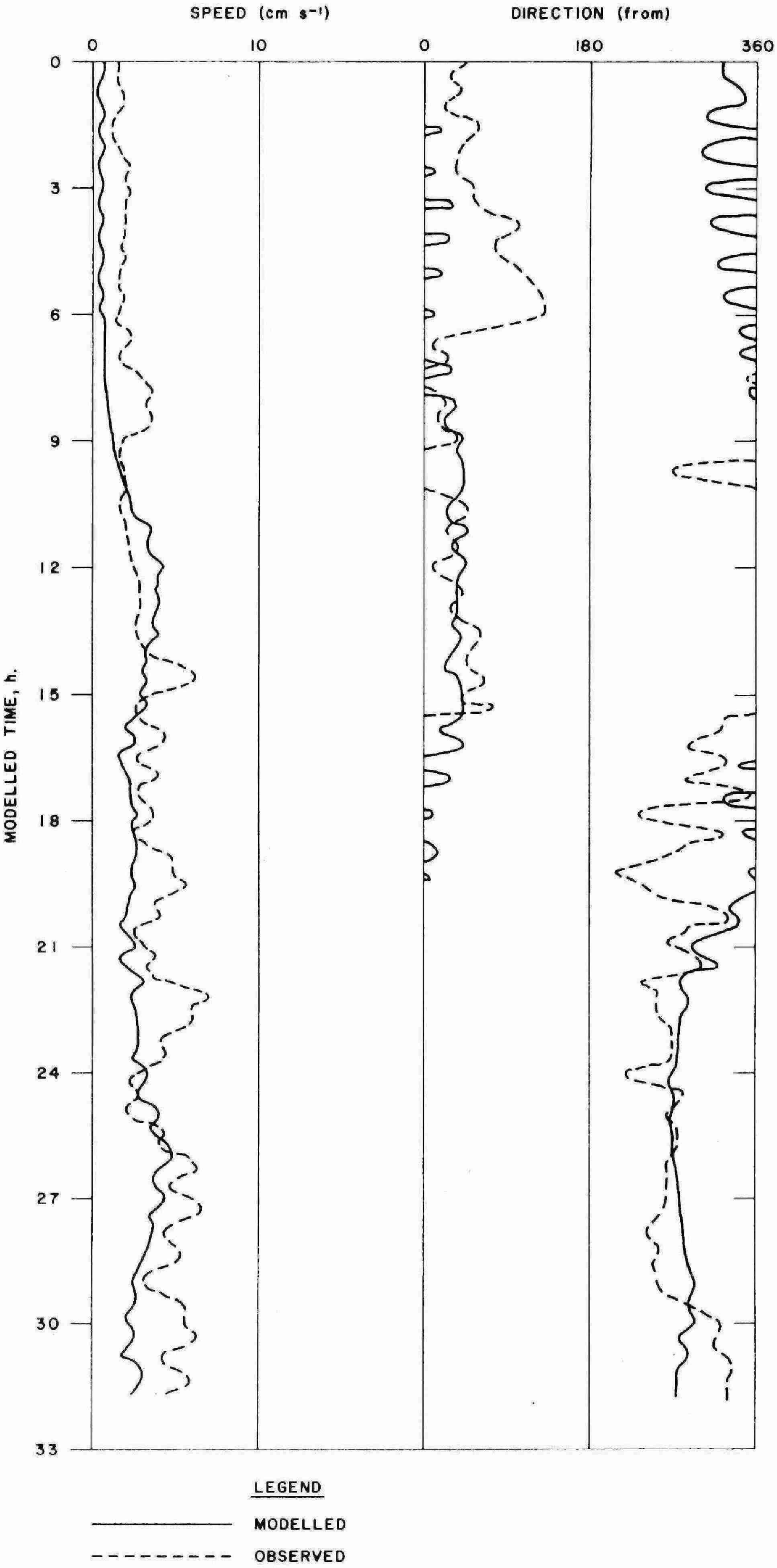


FIGURE 10a – COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT MODEL VALIDATION POINT 'A' FOR 36 h. STARTING AT 0000 h. ON 770706.

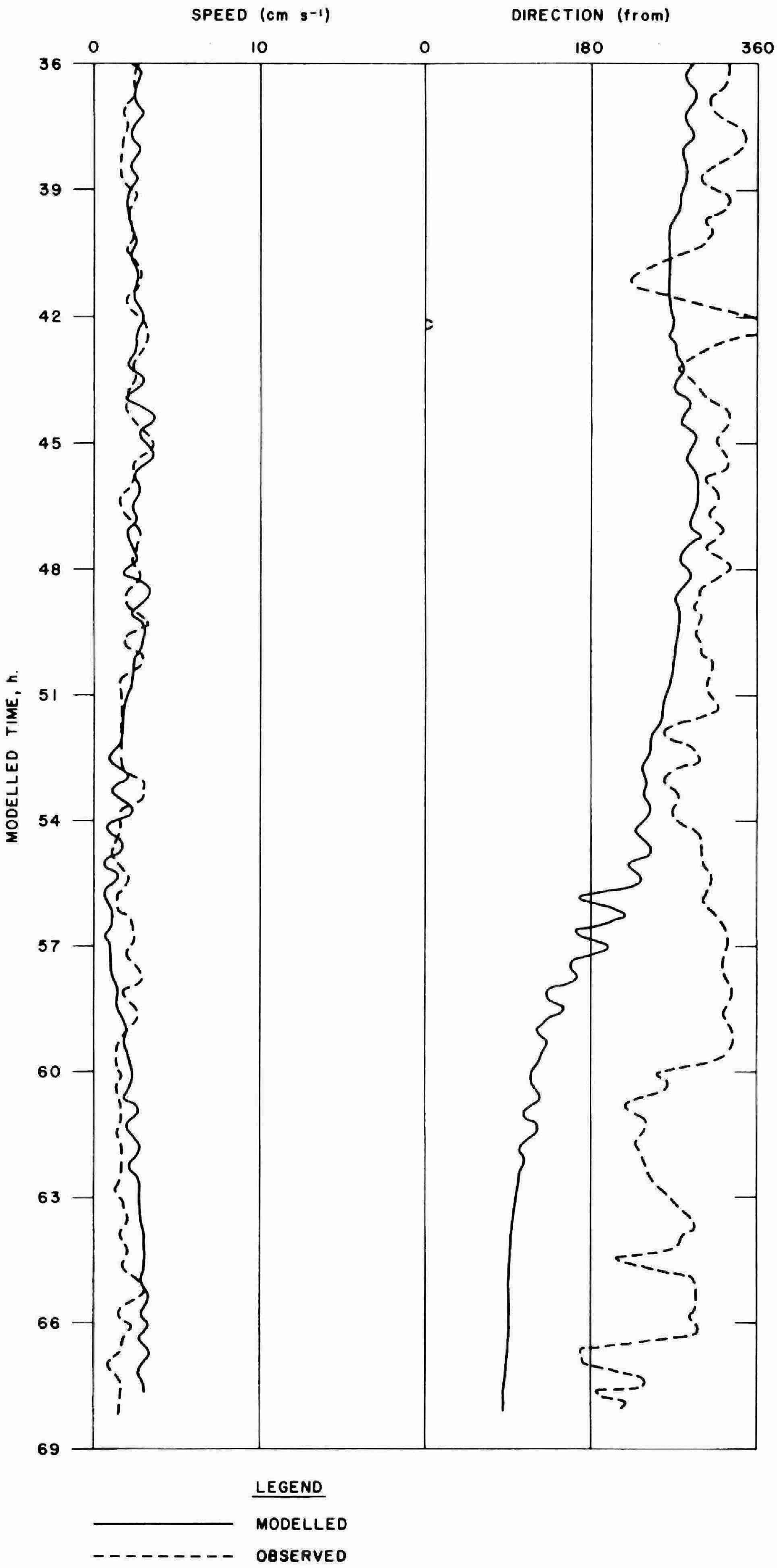


FIGURE 10b – COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT MODEL VALIDATION POINT 'A' FOR 36 h. STARTING AT 1200 h. ON 770707.

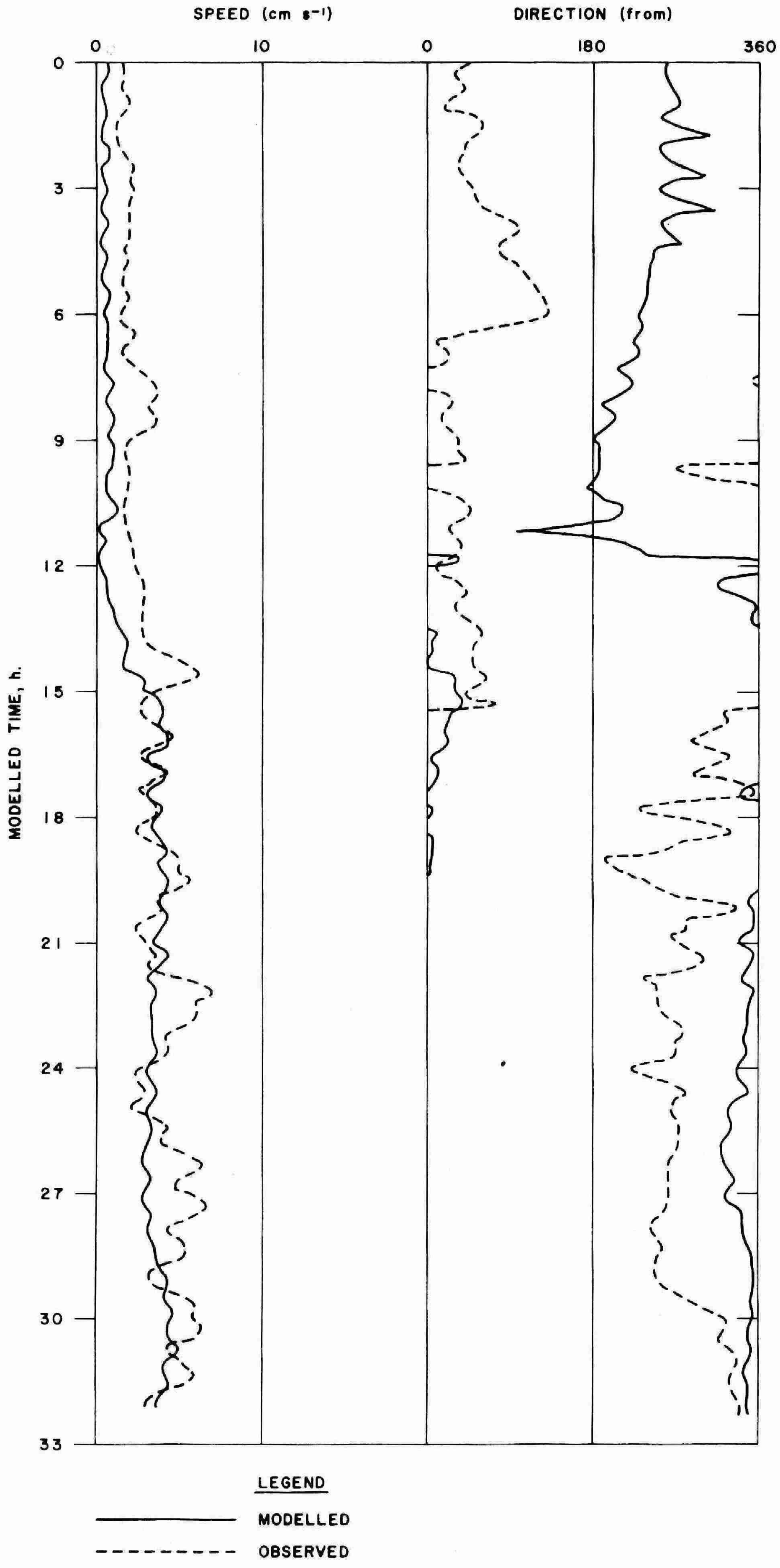


FIGURE 11a - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT MODEL VALIDATION POINT 'B' FOR 36 h. STARTING AT 0000 h. ON 770706.

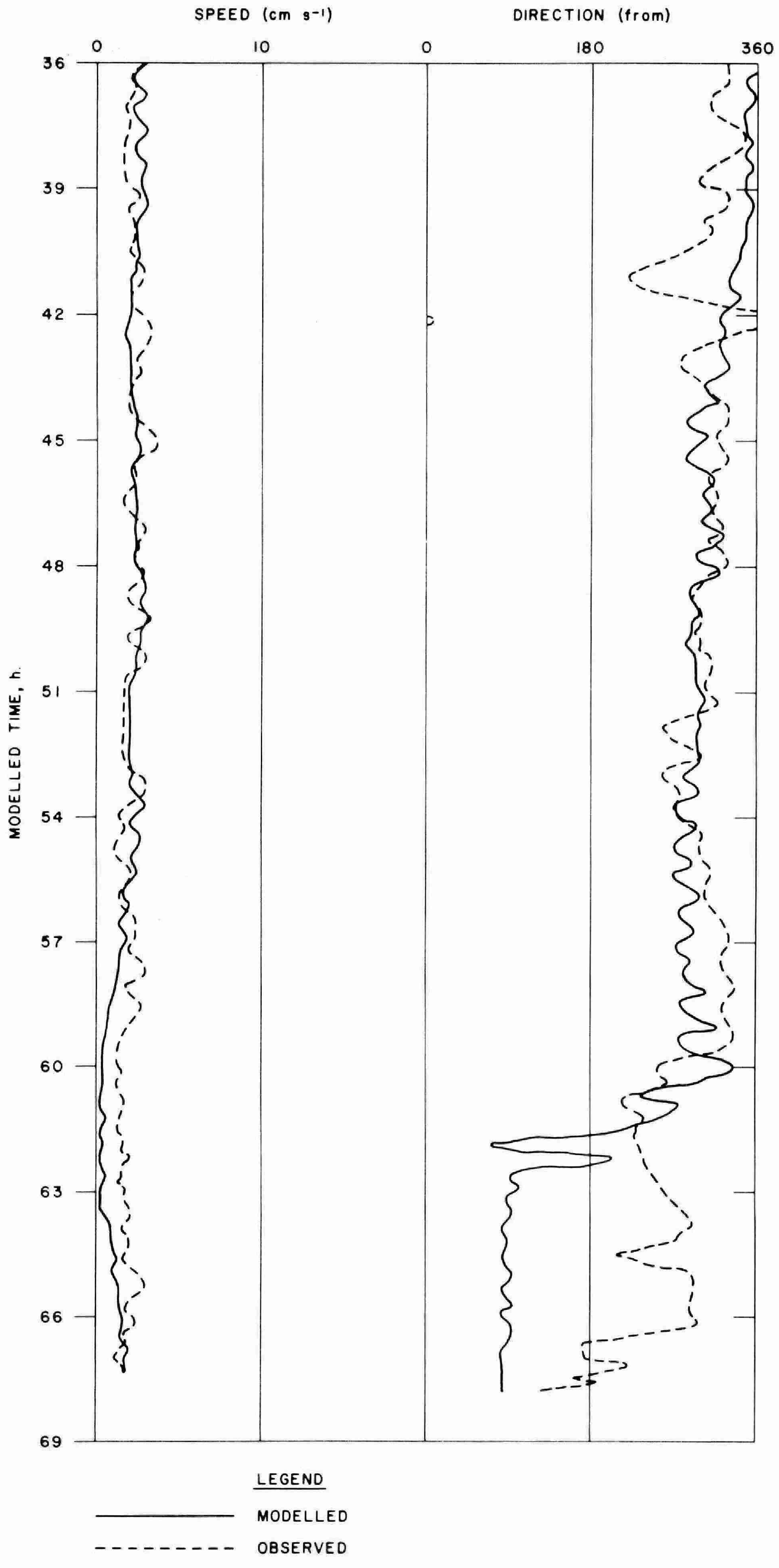


FIGURE 11b - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT MODEL VALIDATION POINT 'B' FOR 36 h. STARTING AT 1200 h. ON 770707.

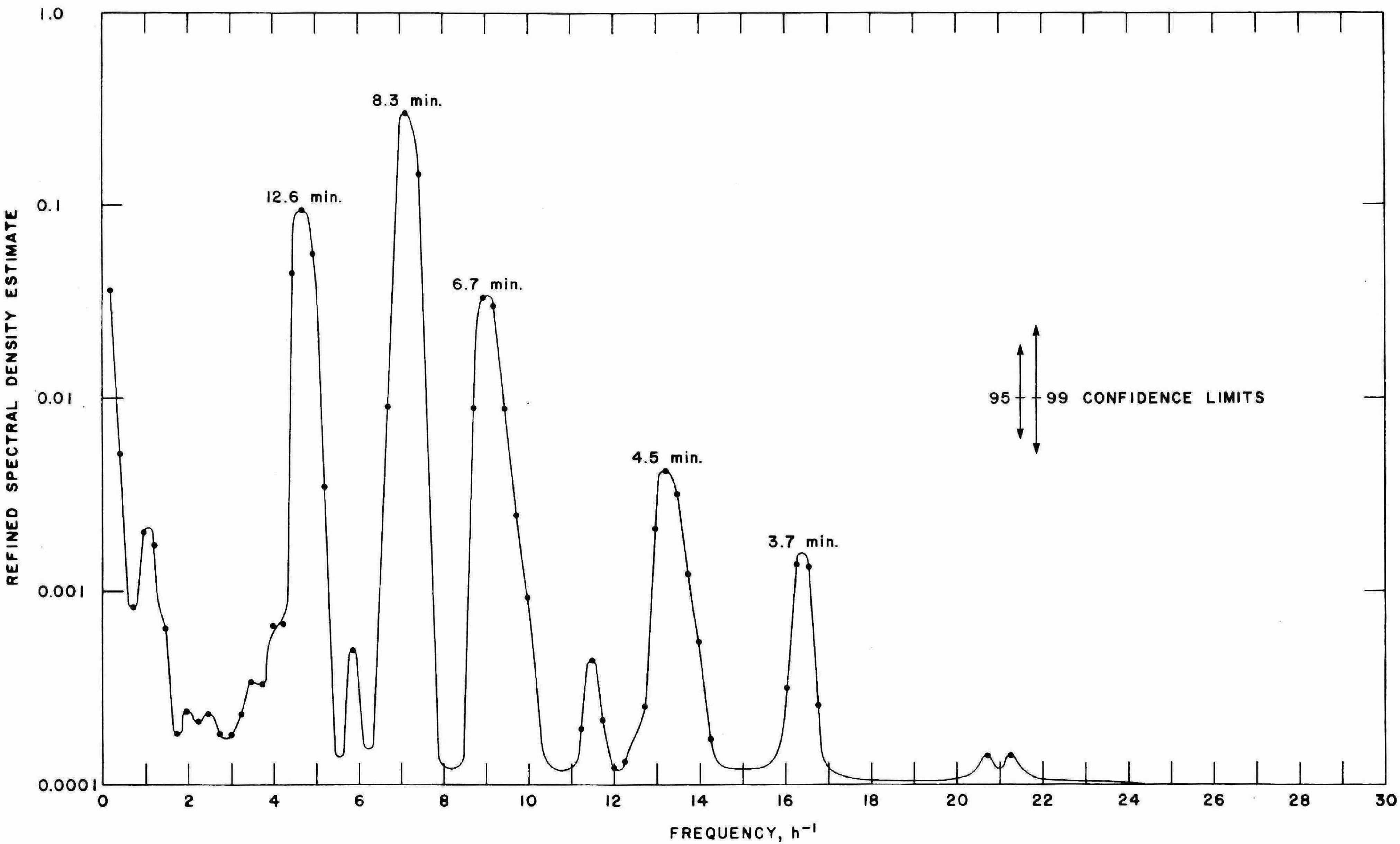


FIGURE 12a - AUTOVARIANCE DENSITY SPECTRA OF MODEL 'U' VELOCITY AT VALIDATION POINT 'A'.

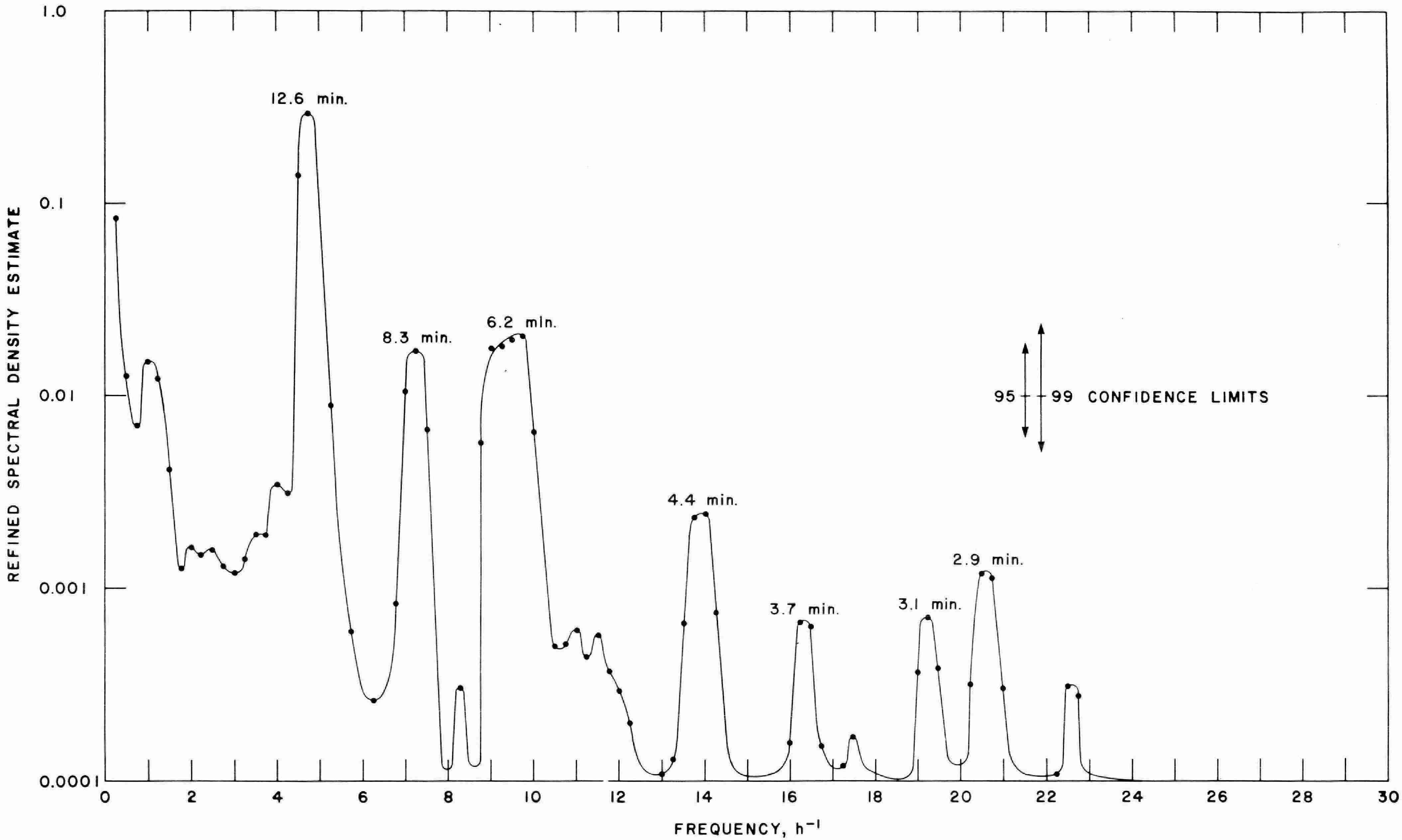


FIGURE 12b - AUTOVARIANCE DENSITY SPECTRA OF MODEL 'V' VELOCITY AT VALIDATION POINT 'A'.

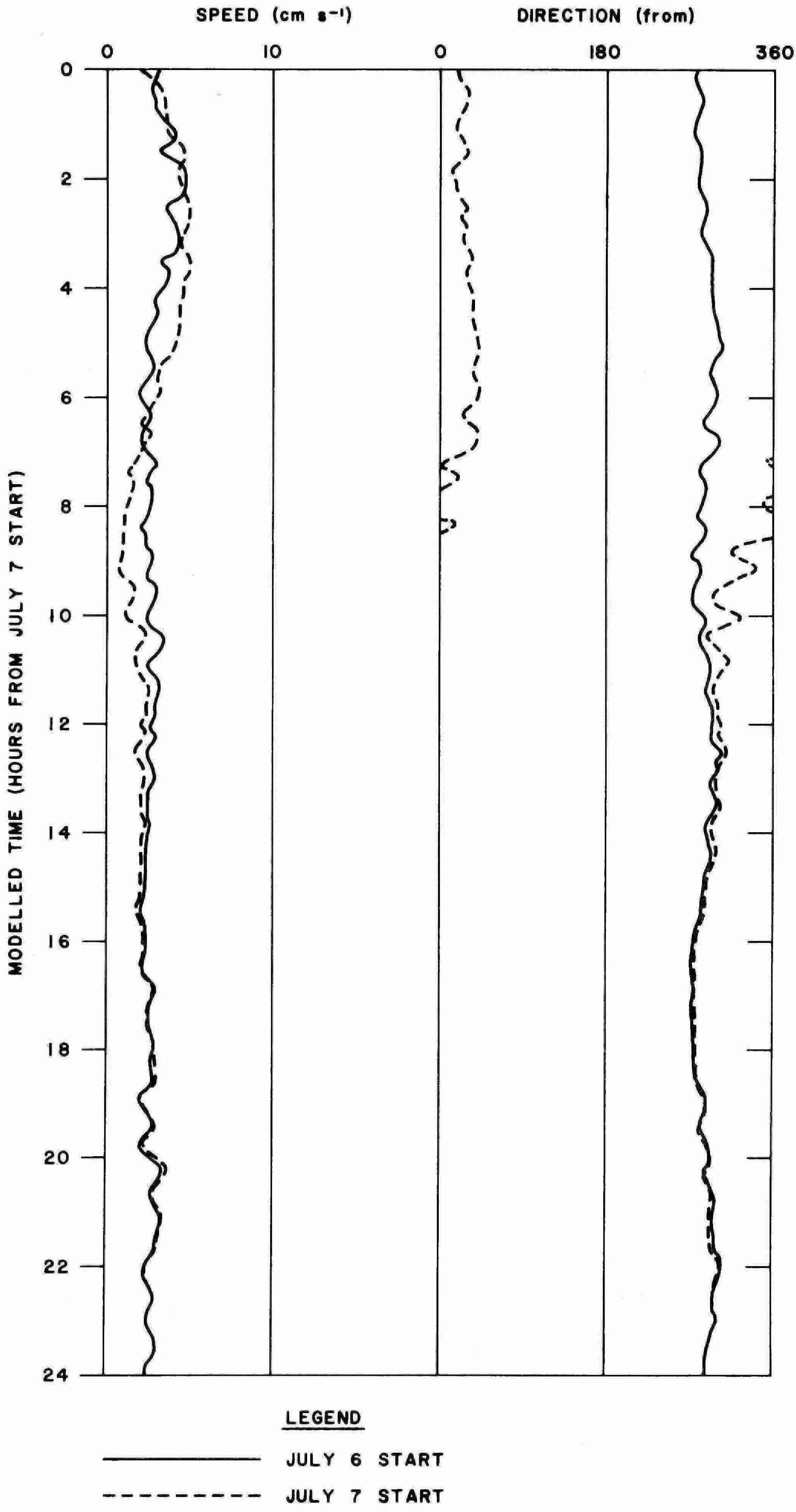


FIGURE 13 - COMPARISON OF MODEL SPEED AND VELOCITY AT POINT 'A' FOR 24 HRS. ON JULY 7, FOR TWO DIFFERENT MODEL STARTING TIMES.

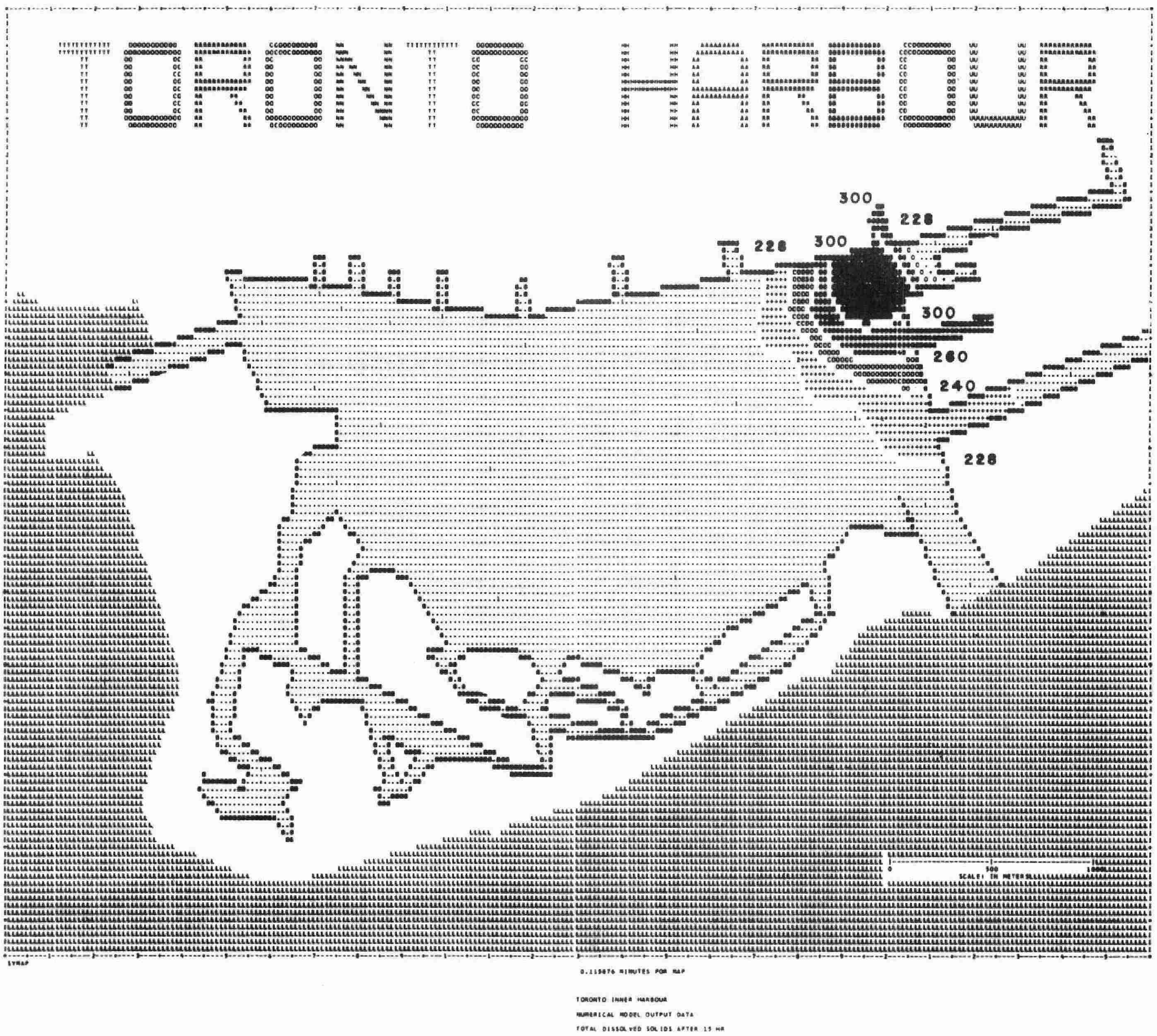


FIGURE 14a - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 15 HOURS, IN THE ABSENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.

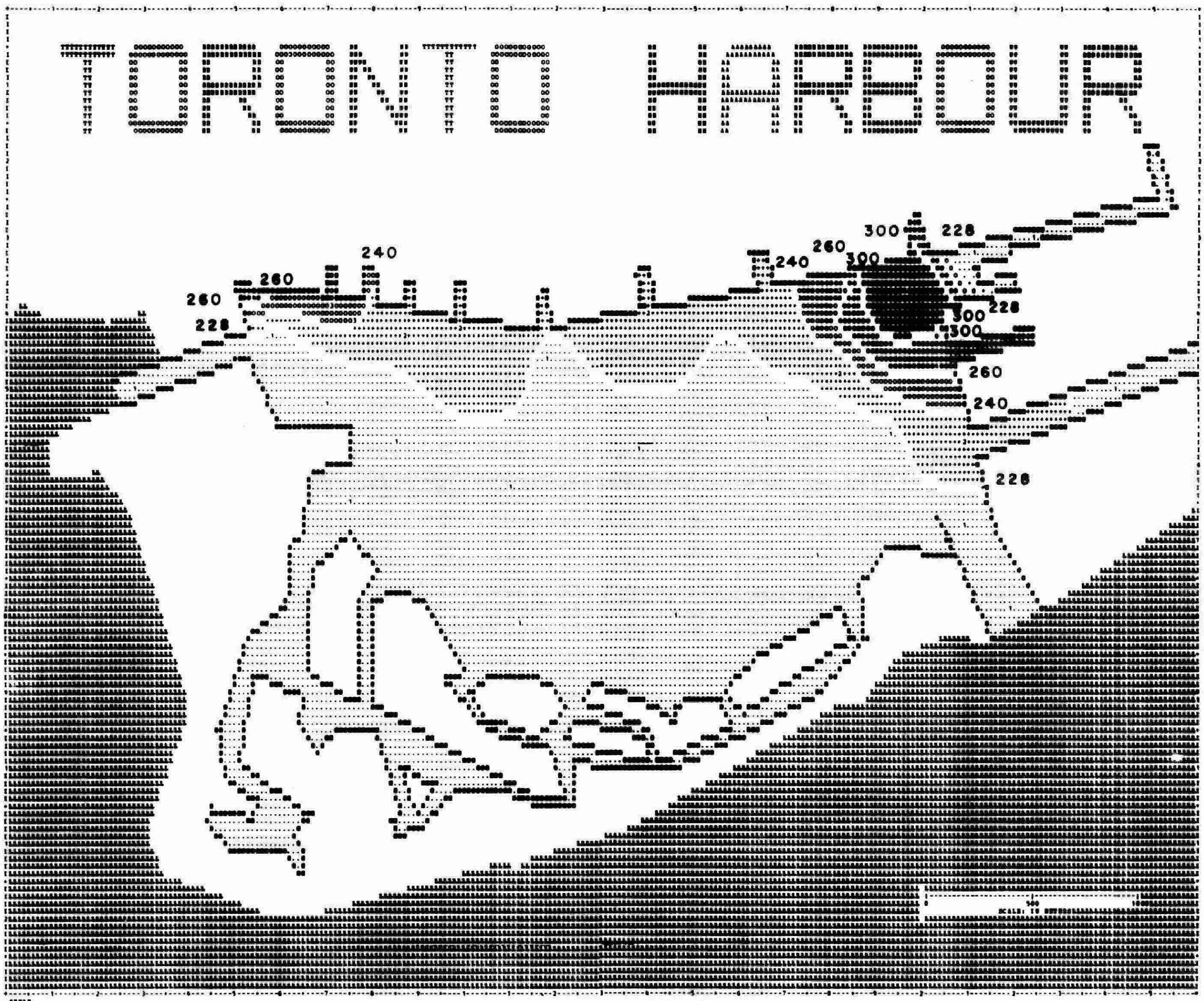
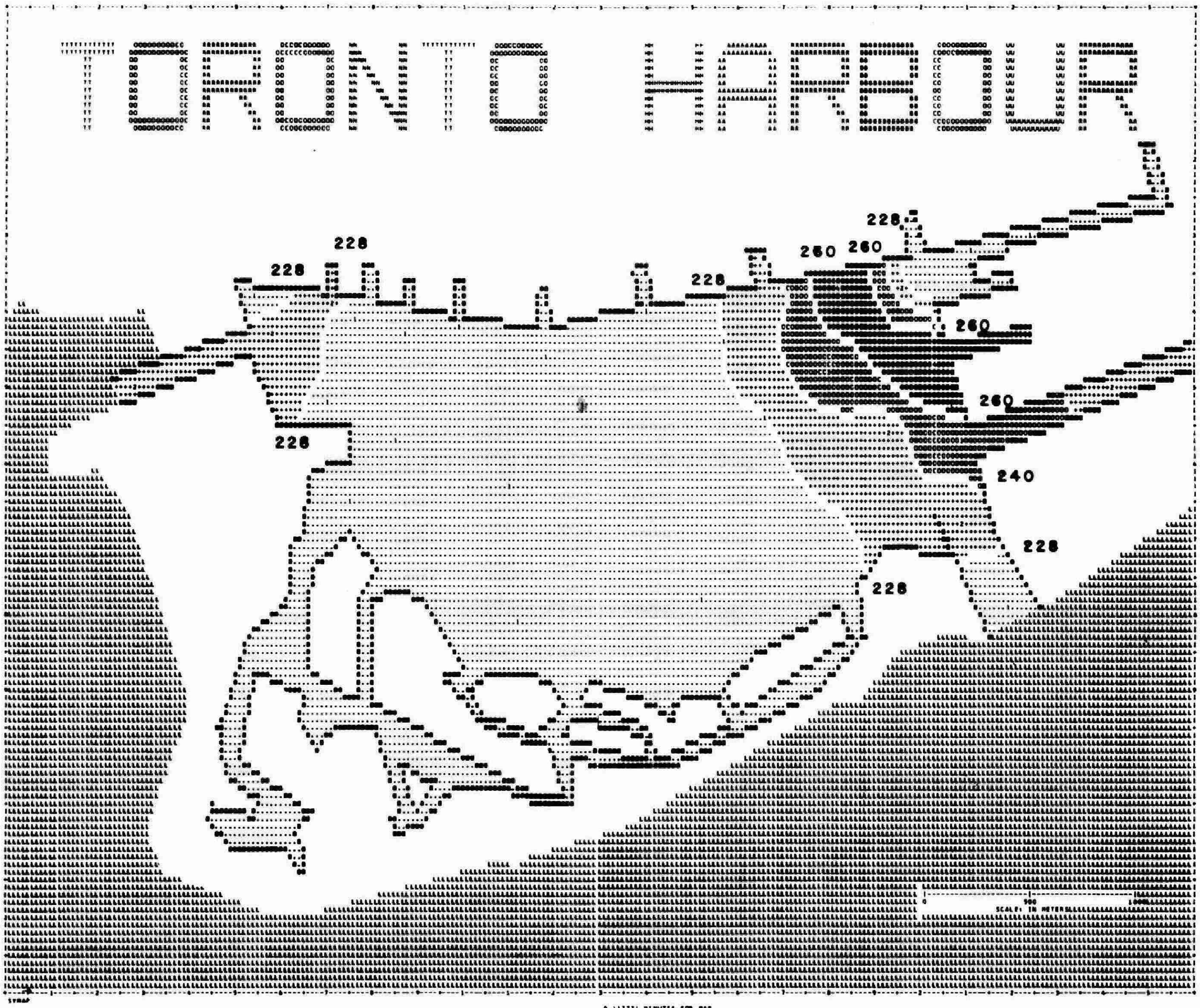


FIGURE 14b - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 15 HOURS, IN THE PRESENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.



0.117771 MINUTES FOR MAP

TORONTO INNER HARBOUR
NUMERICAL MODEL OUTPUT DATA
TOTAL DISSOLVED SOLIDS AFTER 18 HR

FIGURE 15a - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 18 HOURS, IN THE ABSENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.

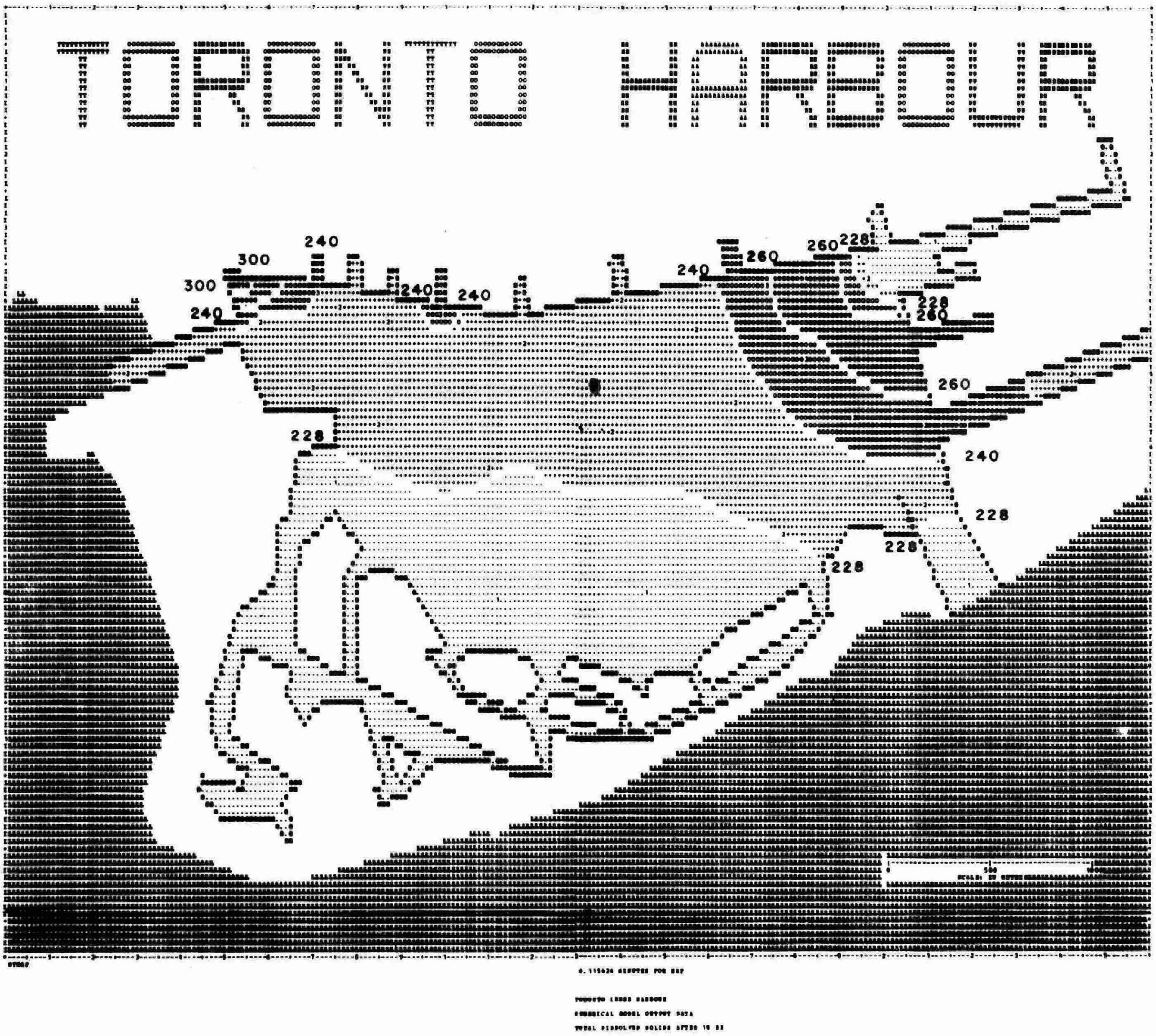


FIGURE 15b - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 18 HOURS, IN THE PRESENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.

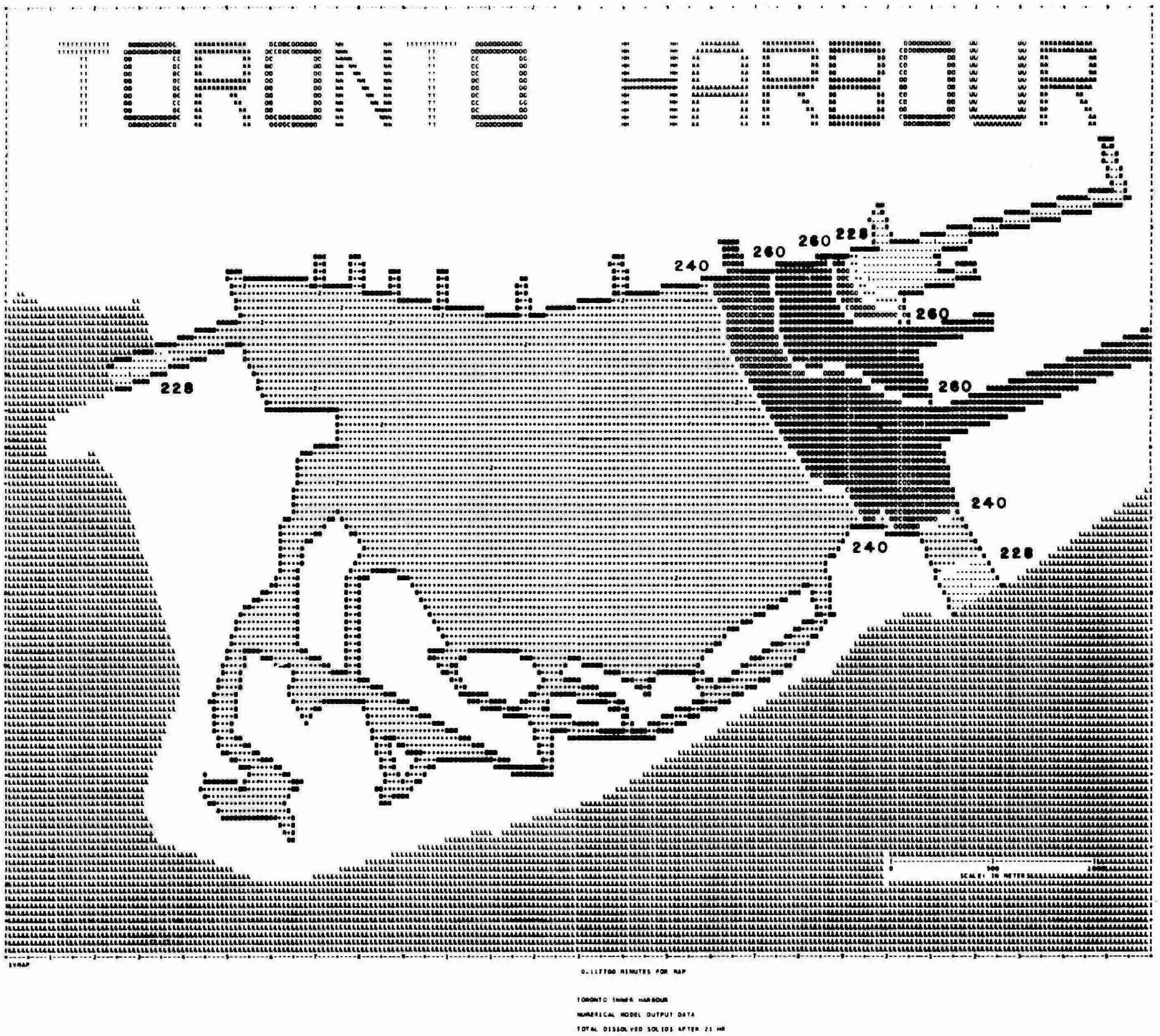


FIGURE 16a - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 21 HOURS, IN THE ABSENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.

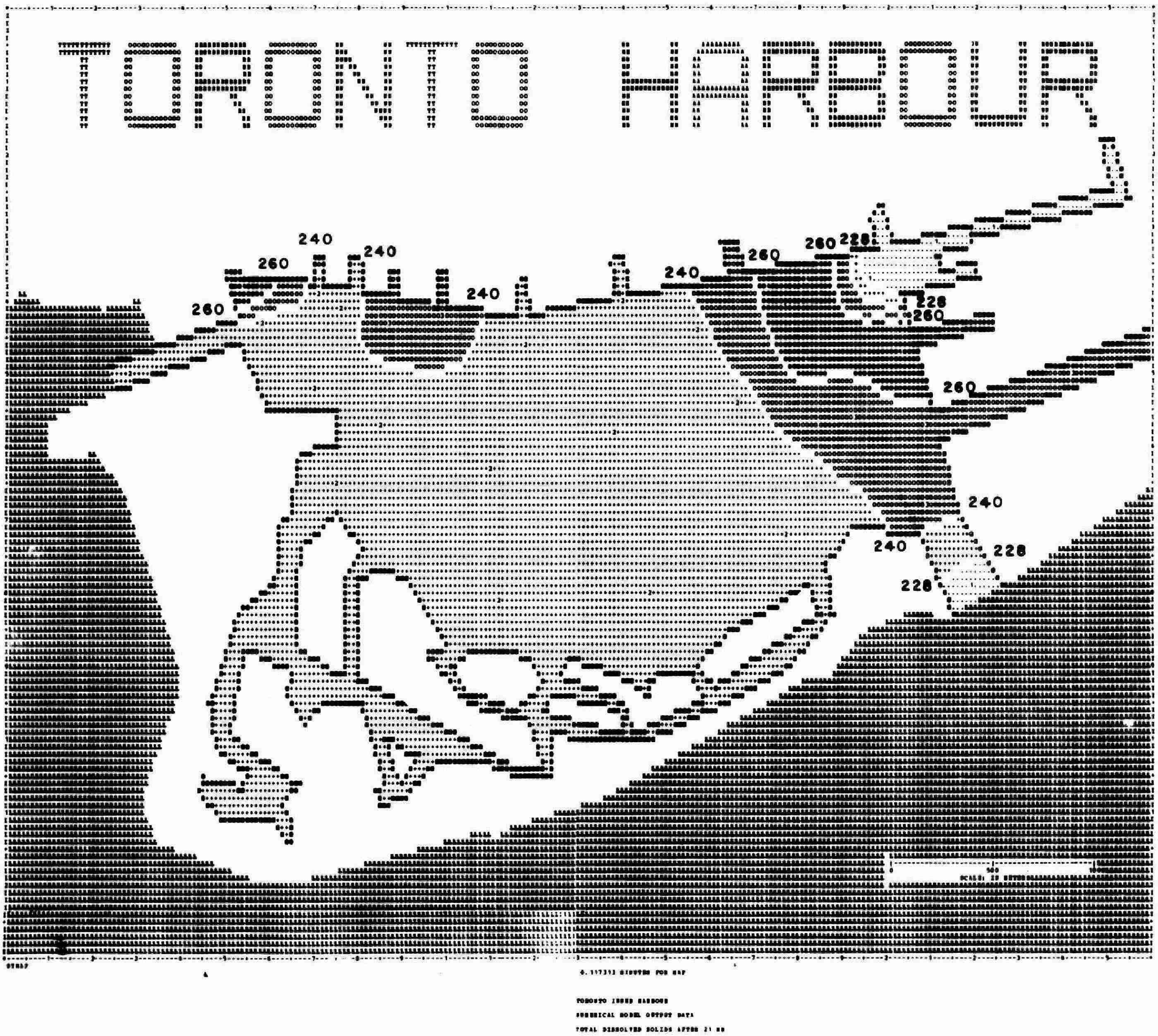


FIGURE 16b - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 21 HOURS, IN THE PRESENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.

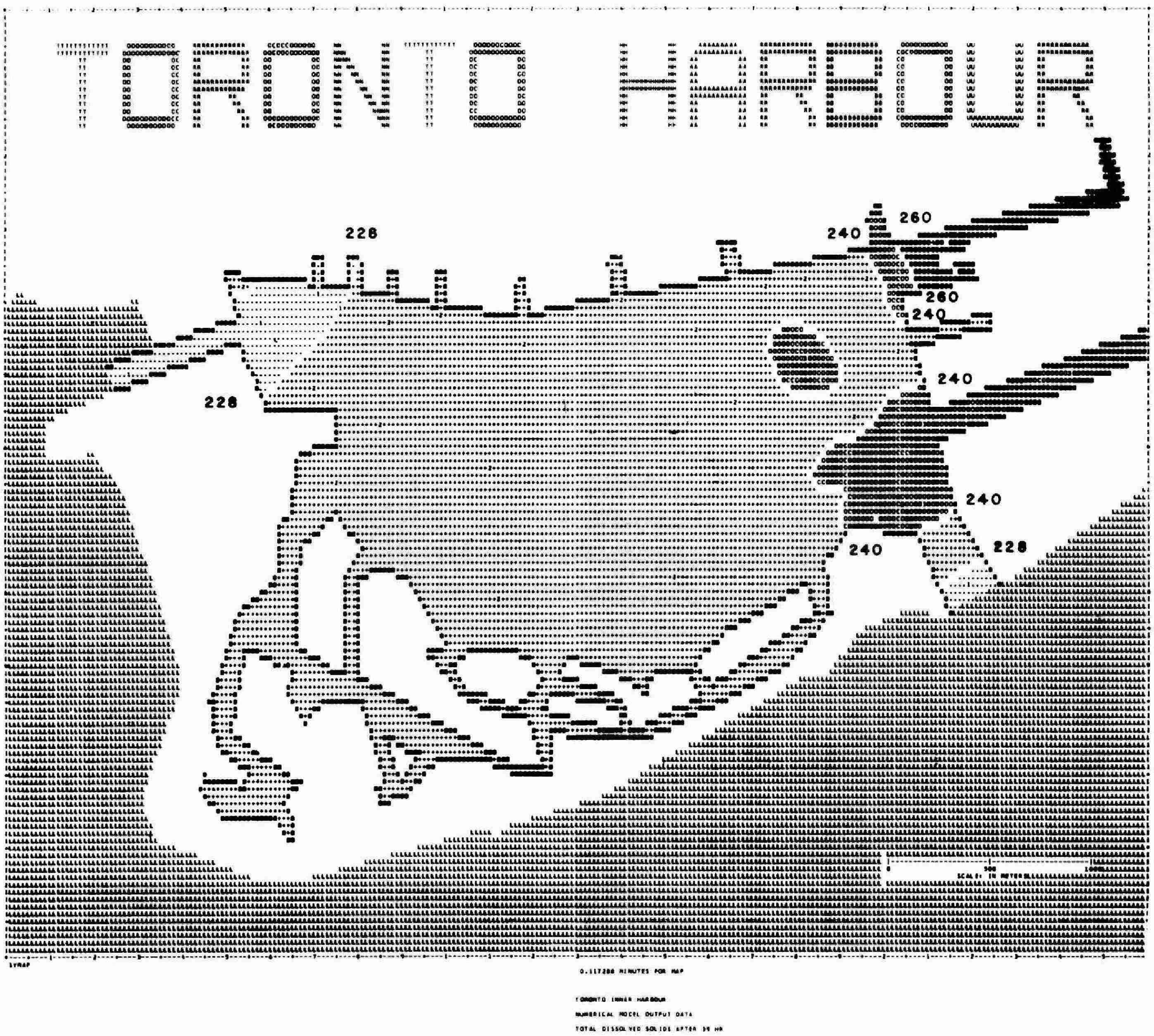


FIGURE 17a - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 39 HOURS IN THE ABSENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.

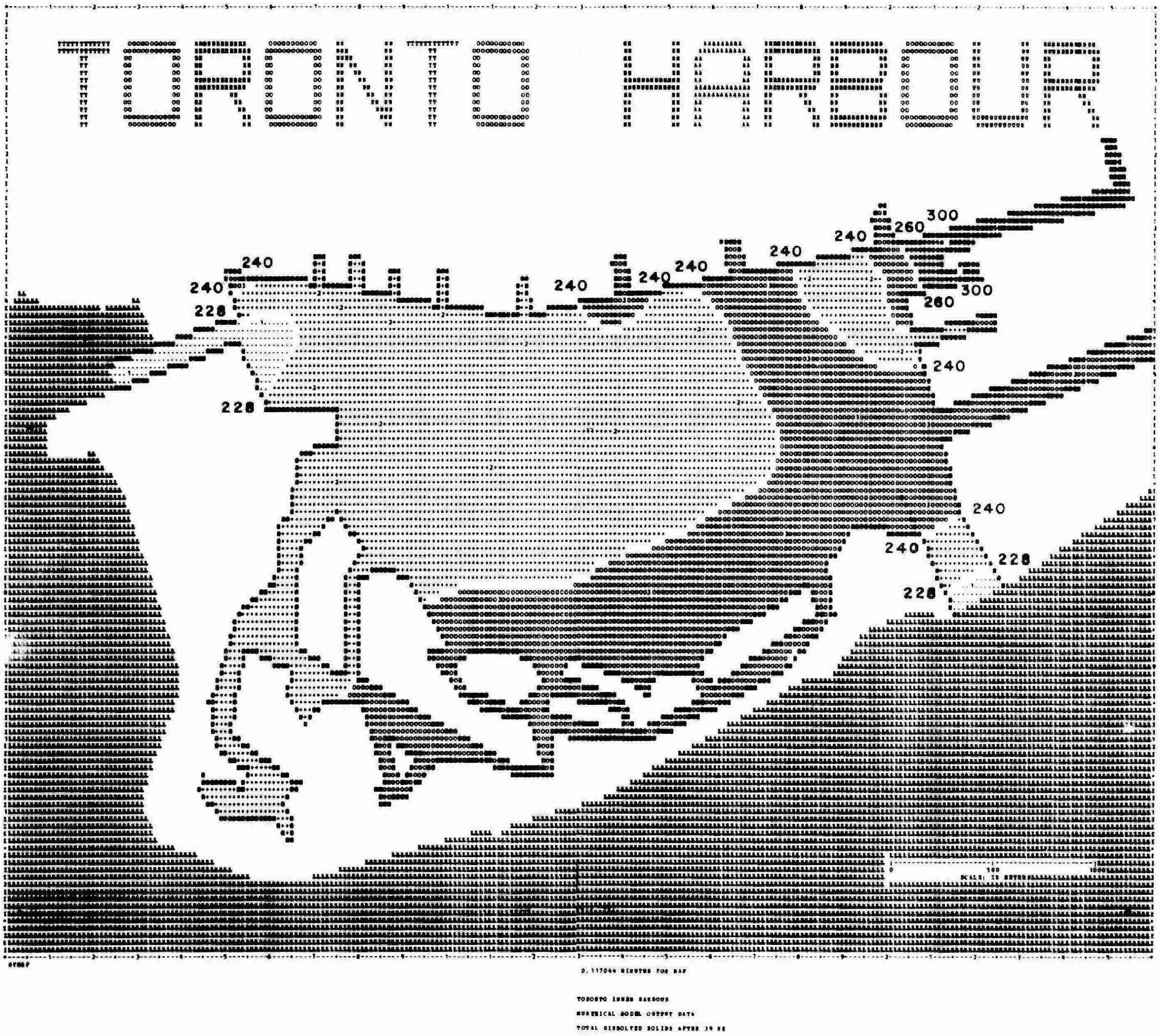


FIGURE 17b - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 39 HOURS, IN THE PRESENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.

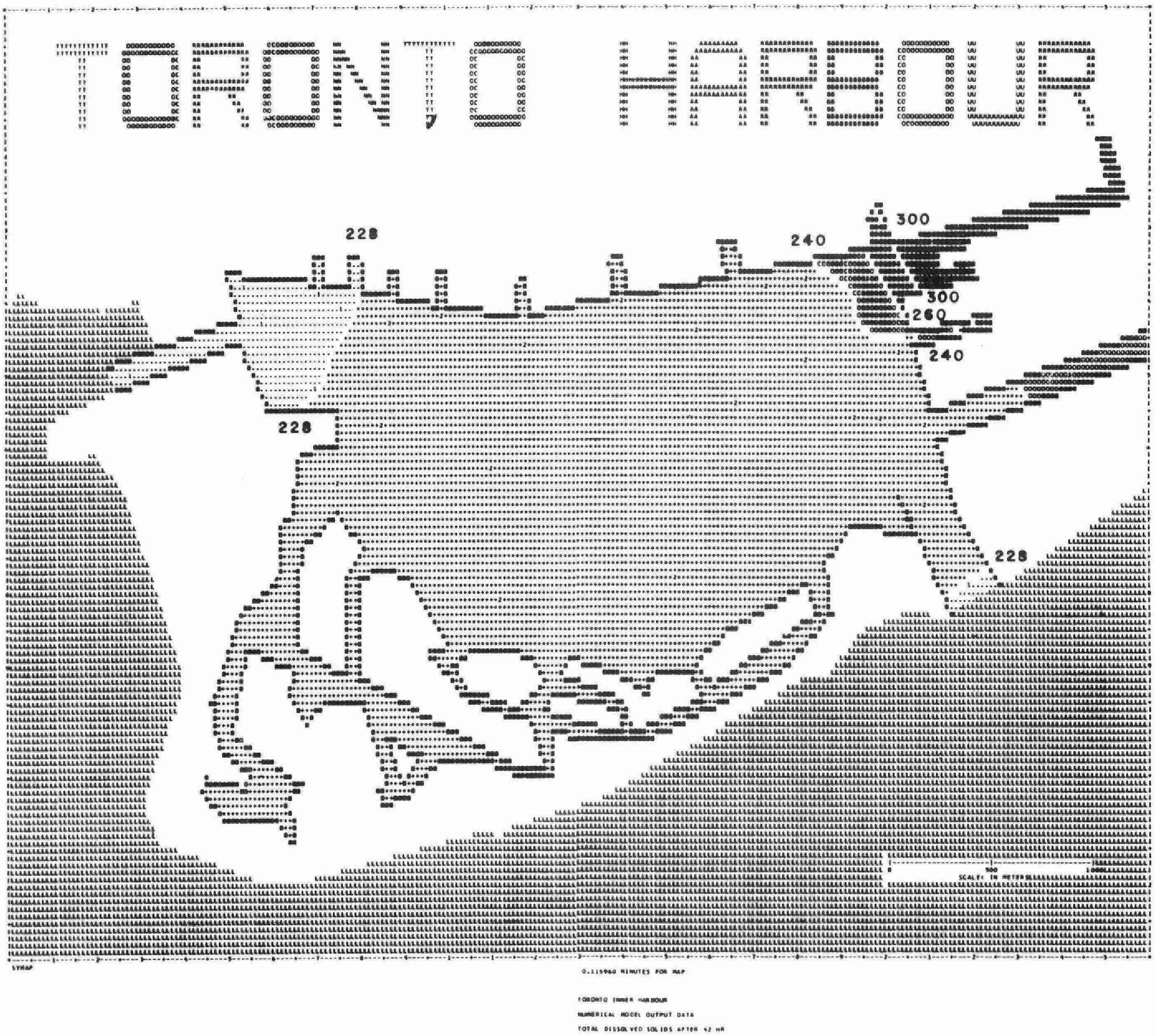


FIGURE 18a - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 42 HOURS IN THE ABSENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.

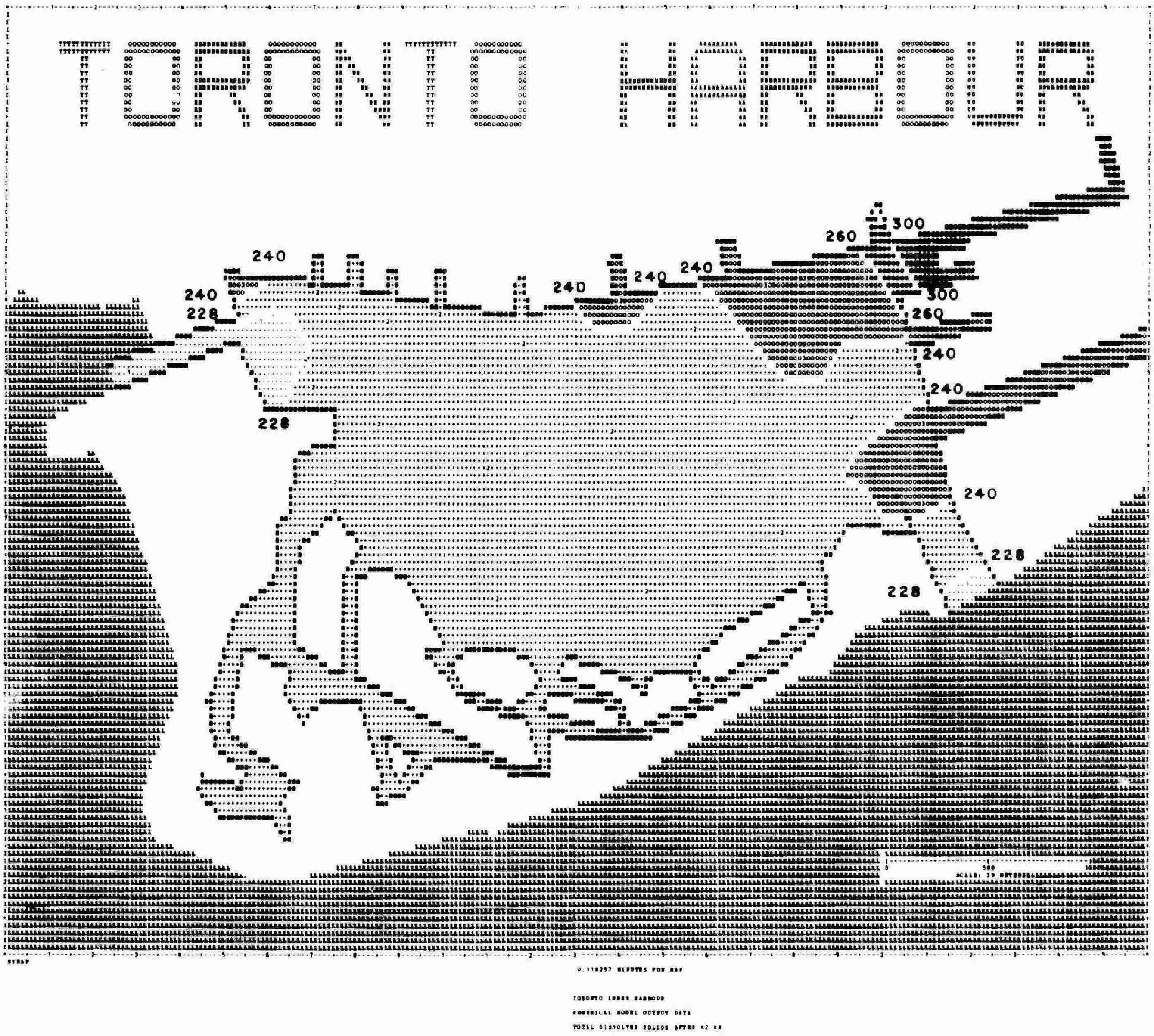


FIGURE 18b - NUMERICAL MODEL PREDICTIONS OF TOTAL DISSOLVED SOLIDS (mg/L) AFTER 42 HOURS, IN THE PRESENCE OF STORM RUNOFF FROM THE CITY WATERFRONT SEWERS.